Cores

CORE ID: 001

Location:		Data Source:	PI
Interval:	2834-2837	Rec:	
Core Type:		Show Type:	
Description:	SANDY SHALE		

CORE ID: 002

Formation:		Data Source:	PI
Interval:	3800-3810	Rec:	
Core Type:		Show Type:	ODOR
Description:	SAND SHALE ODOR		

CORE ID: 003

Formation:		Data Source:	PI
Interval:	4520-4525	Rec:	
Core Type:		Show Type:	
Description:	FINE SAND NO SHOW		

Casing, Liner, Tubing

Casing	Data Source	Size	Base Depth	Cement
CASING	PI	6 5/8 IN	3,460 FT	
CASING	PI	8 IN	2,170 FT	

Drilling Journal

Show

	Data Source	Top Depth	Base Depth	Type	Top Form	Base Form	Sample
	PI	3,503	3,503	OIL			
2	PI	3,800	3,810	ODOR			

Dwights Energydata Narrative

Accumulated through 1997

Old Information

Spud Date:	Sep 28, 1928		Data Source:	PI
Old TD:	3,220 FT		Data Source:	PI

42245600140300

General Information
TH MCFADDIN

Data Source:	PI	Country:	UNITED STATES
API:	42245600140300	IC:	
State:	TEXAS	County:	JEFFERSON
Field:	WILDCAT	Operator:	DEEP TEST INCORPORATED
Current Status:		Current Operator:	DEEP TEST INCORPORATED
Initial Class:	NEW FIELD WILDCAT REDRILL (WFR)	Final Well Class:	NEW FIELD WILDCAT-DRY (INCLUDING TEMPORARILY ABANDONED WELL) (WF)
Status:	D&AW	Target Objective:	
Permit:	on Feb 11, 1931	Hole Direction:	VERTICAL
First Report Date:	Aug 15, 1931	Abandonment Date:	
Projected TD:		Projected Formation:	
Basin:	GULF COAST BASIN	Formation at TD:	
Play Name:		Play Type:	

Location

Footage NS EW Origin:	200 FS 770 FE TX SUR/POR/GRANT		Data Source:	PI
Dist, Abs, Survey:	RR DISTRICT 03 435	J & J CHAISSN 12		
Blk, Lge, Lot, Labor:				
Township, Section:				
Lat/Long:	+30.0371293 -94.0510413	Lat/Long Source: IH	Datum:	NAD27

Dates and Depths

Data Source:	PI		
	Feb 21, 1931	Spud Date Code:	
	3,156 FT	TD Date:	
TVD:		PlugBack Depth:	
Formation Code TD:		Formation Name TD:	
Ref. Elevation:		KB. Elevation:	
Ground Elevation:	23 FT EG	LTD:	
Contractor:			
Completed:	Aug 01, 1931	Final Drilling:	
Rig Release Date:		Rig #:	
Tool:	CABLE		

Drilling Journal

Dwights Energydata Narrative
Accumulated through 1997

Old Information

Spud Date:	Feb 21, 1931		Data Source: PI
Old TD:	5,390 FT		Data Source: PI

APPENDIX 4-4

APPENDICES

Appendix 4-4 thru 4-20

(AOR Book 5 of 5)

Appendix 4-4

Artificial Penetration Protocol & Model

APPENDIX 4-4

DOW BEAUMONT ANILINE UNIT

AREA OF REVIEW

ARTIFICIAL PENETRATION PROTOCOL

Dow Petition Reissuance 2020   4-4-1   *Dow Beaumont Aniline*
GeoHydroLogicPro, LLC   *Frio Reissuance No-Migration Petition*
October 31, 2018

Section 4- Area of Review   4-4-2   *Dow Beaumont Aniline*
GeoHydroLogicPro, LLC   *Frio Reissuance No-Migration Petition*
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1.0 ARTIFICIAL PENETRATION PROTOCOL

The Area of Review is the area within which the owner or operator of Class I injection wells must identify all artificial penetrations that penetrate the confining or injection zones. For purposes of the UIC program "Non-Endangerment" standard, the Area of Review under the Federal regulations is defined as a fixed 2.0 mile radius around the injection well unless the Director specifies a larger radius. Wells within this Area of Review are then evaluated to ensure that abandoned boreholes will not provide a pathway for injection-induced movement of fluids into a USDW.

For purposes of a "No-Migration" demonstration, an additional and different "Area of Review" is also considered. This area of review consists of the area within which - based on reasonable worst case projections - the injectate plume may be located at any point within the next 10,000 years. Wells located within this area of review are evaluated in order to demonstrate that abandoned boreholes will not provide a pathway through which injected fluid constituents could migrate from the injection zone.

The following is an outline of the steps that were taken to identify and evaluate artificial penetrations for purposes of both the "Non-Endangerment" and "No-Migration" standards.

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2.0 WELL IDENTIFICATION

2.1 Data Sources

A specific and consistent methodology was used to identify all artificial penetrations within the Area of Review surrounding the DuPont Beaumont Works. Several data sources were utilized to locate pertinent information regarding each artificial penetration. Revised or updated base maps from Tobin Surveys, Inc., Cambe Geological Services, Inc., and the Jefferson County oil and gas base map maintained by the Texas Railroad Commission were utilized to initially identify and establish a general background on the wells in the Area of Review. State agency files along with state libraries were researched by Agency Information Consultants (AIC), Geosource Incorporated (GI) and/or R.W. Byram & Company for descriptive well documentation. The regional libraries of Cambe Geological Services, Inc., a commercial log service company, were researched for well logs and scout tickets applicable to each well identified in the Area of Review. Additional records data were obtained through the University of Texas, Balcones Research Center. Where discrepancies existed among data sources, state form data were considered to be the most accurate. Since the Petition was approved in 2001 various updates have been provided by Banks Information and D-B Associates of Austin, Texas. The following discussion is a synopsis of the procedures used to procure these state form data.

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3.0 FILE SEARCH AND RESEARCH PROCEDURES FOR THE TEXAS RAILROAD COMMISSION

The well record filing system of the Texas Railroad Commission is cumbersome due to changes in filing procedures implemented through the years. The enormous amount of information contained within the system has often been reorganized when directors of the Texas Railroad Commission have changed. The following discussion on file searches and research procedures for the Texas Railroad Commission outlines the necessary steps that must be taken in order to retrieve oil and gas well records to be used in researching each well within a given area.

3.1 Maps

Before the retrieval process can begin, it is necessary to know the operator, lease name, and county in which the well is located, and the name of the survey in which the well is found. The preceding information is normally found on commercially prepared oil and gas base maps. The Texas Railroad Commission maintains county and field maps used by the researcher to determine operator, well name, approximate drilling date, and field name.

County maps are produced by commercial firms, who obtained the data to build the oil and gas bases from scout tickets, completion data obtained from individual oil companies in the early years, and then, in later years, from the Texas Railroad Commission itself. The Texas Railroad Commission purchases these maps and utilizes them as base maps, plotting incoming information filed by oil and gas operators. Changes in the status of existing wells are noted, as well as factual material on new wells.

Field maps are prepared by Texas Railroad Commission personnel from the commercial base maps. Field maps are prepared when there is an extremely high well concentration in an area and it is necessary to expand the scale of the area so that wells can be properly identified. All data including survey name, fee name, acreage and configuration of tracts of land, operator name, and well location are taken from the county map and transposed onto the field map. Once the field map is prepared, any wells drilled, deepened, plugged back, or plugged in the area encompassed are spotted on this map.

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The researcher should utilize both types of maps on file with the Texas Railroad Commission as well as other available commercial oil and gas base maps. The information found on these various base maps is used to proceed to the next step of the research process.

3.2 Microfilm Records

All records filed with the Texas Railroad Commission prior to 1973 are found on microfiche and microfilm. Records in some Texas Railroad Commission districts are filmed through 1980. These microfiche and microfilm records are organized in several different systems, such as operator and lease name, or district, field, and operator name, or district, field, and lease number. Within these systems, a large number of exceptions to the filing procedures create additional filing sub-systems.

The standard film sets available are a) unit cards; b) well records-folders rolls; c) well records-runs 20-30 and A-I; d) well records-major runs; e) well records-old warehouse film; f) well records-K, L, M runs; g) potential film; h) wildcat and suspense film; i) well record files; and j) suspense files. Each is discussed individually below.

3.3 Unit Cards

Unit cards are microfiche records for wells which had records filed with the Texas Railroad Commission prior to 1962. These units are filed sequentially by an operator number assigned by the Texas Railroad Commission when the operator filed the required organization report with the agency. The operator number can be referenced in either the county book or the county microfiche. There is a county book maintained for each county within the state. Within the county book, the information is organized alphabetically by lease name which cross references to the operator name and corresponding operator number. The county microfiche are a recent addition to the Texas Railroad Commission filing system. The agency took the county books and reorganized the leases into alphabetical order and microfilmed the information. Although the county books are not organized as neatly as the county microfiche, they are the original system and are more accurate due to unintentional omissions made when reorganizing the listings.

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Operator numbers can also be obtained from old copies of organization ledgers maintained by the Texas Railroad Commission. These ledgers are in five separate sets which correspond to various time periods from the 1920s to the 1960s. These ledgers list only operator names, addresses, and numbers assigned by the agency, and are used as a last resort, since they do not indicate lease names and often list multiple operators with the same name.

Once the operator name is matched to a lease name and an operator number is given, the unit card, if available, is pulled. The lease names are filed alphabetically within each operator number. Since there are exceptions to the filing system, if the desired information is not available or only partially available on the unit card, then the researcher must proceed to the next set of microfilm.

3.4 Well Records Folders Rolls

Duplicate copies of unit cards, which sometimes contain information that was not included in the initial filming of the unit cards, are referenced on the folder rolls. The folder rolls are organized by operator number and folder number which appear on the unit card jacket. In addition, some folder rolls do not have a folder number given, but only an operator number. These rolls are called "addon rolls" and also contain records not included in the initial filming of the unit cards.

3.5 Well Records Runs 20 to 30 and A to I

These rolls are organized by operator number and by specific periods of years. These rolls encompass a period from 1945 to 1960 and commonly have three to five rolls for a specific year and operator number. When information is not available on the unit cards, these are the next set of film to be researched for records.

3.6 Well Records Major Runs

These are a special set of film that contain only information on records filed by major operators. These rolls are organized by operator and then alphabetically by lease name. It should be noted that there are very few unit cards for major companies and that, if any information were filed on a lease or well, it would be found on this set of film. It should

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also be noted that major operators, even in the early years of the oil business, were very prudent about filing completions and plugs for wells which they operated.

3.7 Well Records Old Warehouse Film

This set of film contains some of the earliest information filed with the Texas Railroad Commission and includes oil and gas well records filed from 1919 to 1939. There are only five rolls of this film, with three rolls organized numerically by operator number and two rolls organized alphabetically by operator name.

3.8 Well Records K, L, and M Film

In March 1966, the Texas Railroad Commission instituted a new filing system. However, before the system could be fully implemented, many well records which were filed during the period of transition were placed onto the K, L, and M film. The K Run covers portions of records filed from 1963 to 1964, the L Run covers portions of records filed from 1964 to 1965, and the M Run covers portions of records filed from 1965 to March 1966. The K, L, and M film is organized by operator number, with leases listed alphabetically within operator number.

3.9 Potential Film

In March of 1966, the Texas Railroad Commission filing system was converted to the potential filing system, which is used today. This film contains records of all wells that produced oil and/or gas and were placed in a designated oil or gas field. This film is organized by Texas Railroad Commission District, field name, and oil lease number or gas well identification number.

3.10 Wildcat and Suspense Film

This film contains records of all wells with applications to drill in wildcat fields or new leases in designated fields that were on leases that did not have a lease identification number previously assigned due to no producing wells on the lease in the field. This film is organized by district, county, and/or American Petroleum Institute (API) number. The API numbering system has been in effect since April 1966. The numbers have been stored within the Texas Railroad Commission computer system as well as being noted on

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all forms filed for the well. The system allows information to be retrieved by computer showing drilling status, operator, lease name, oil lease number or gas identification number, and field name. This is a very efficient system and allows quick and accurate retrieval of data filed since 1978.

3.11 Well Record Files

These are the hard copy files of data not yet placed on microfilm. These files are organized by district, field name, and oil lease number or gas identification number. These files contain the most recent data processed by the Central Records staff of the Texas Railroad Commission. Inside these folders are references to data that have been placed onto potential film.

3.12 Suspense Files

These files contain the most recent information to be filed with the Central Records Department. This is the holding area for information to be placed into existing well record files or to have new oil lease or gas identification files prepared. The information is filed by district and API number. To obtain API numbers assigned to these records, it is necessary to search suspense cards that are filed by district, county, and alphabetically by lease name. Records that have not been placed in suspense files are usually found within the Map Department where they are held until data are placed on the county oil and gas base maps or on field maps.

The aforementioned record sets are the primary file systems utilized to access records in the Texas Railroad Commission. In retrieving information from the Texas Railroad Commission, the researcher often has to examine every file system available in search of a particular piece of information.

4.0   EVALUATION PROCEDURE FOR ARTIFICIAL PENETRATIONS

4.1   Well Type

Once identified, the artificial penetrations were subdivided into wells that are abandoned and wells that are active. An abandoned well is a well where use has been permanently discontinued or is in disrepair such that it cannot be used for its intended purposes. These types of wells include dry holes, abandoned production (oil and gas) wells, and injection wells. An active well is a well that is currently operating, including production and injection (saltwater disposal, enhanced recovery or other) wells, or wells which are temporarily shutin (subject to annual integrity testing).

4.2   Well Status

Each artificial penetration (active/abandoned) was evaluated as to the adequacy of construction and plugging to determine the potential of the penetration to convey fluid from an injection interval and zone into the overlying USDWs (Non-Endangerment) and the potential of the penetration to convey injected fluid out of the injection zone (NoMigration). Where construction or plugging did not rule out potential concerns, wells were evaluated or modeled to determine compliance with the Non-Endangerment or No-Migration standards.

4.3   Confining and Injection Intervals and Zone Penetration

Multiple confining shale intervals exist overlying the Frio Sand Injection Interval. The Anahuac Shale is considered to be the primary immediate confining interval present above the Frio Sand, however additional confining shale intervals are present within the lower Miocene Sand section. Only those wells that penetrate the Anahuac Shale confining interval and the Frio Sand Injection Interval could have the direct potential to convey fluid from the injection interval to an overlying USDW. Available geophysical well logs for the artificial penetrations present within the Area of Review were correlated to determine which of the wells actually penetrate the confining/injection interval. Wells that do not penetrate this interval therefore, do not provide potential avenues for fluid movement and thus are not considered as artificial penetrations, therefore, they need not be further evaluated.

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4.4   Rock Types

Unconsolidated rock formations such as the geologically young shales in the Gulf Coastal Plain have hydration due to expanding smectite clays (such as those present beneath the DuPont Beaumont Works) and plastic properties which result in natural closure of man-made boreholes (Johnston et al., 1979), (Davis, 1986), and (Clark, et al., 1992). Johnston and Knape, 1986, reported, after interviewing several experienced drilling engineers, that the geologically young and unconsolidated sediments of the Gulf Coast tend to slough and swell, and an uncased borehole will commonly squeeze shut within a matter of hours, resulting in natural borehole closure. Agency Information Consultants, 1987, examined improperly plugged abandoned wells in over 46,500 Texas oil and gas fields in both unconsolidated and consolidated regions, and documented natural closure as an important mechanism in preventing upward fluid movement in the unconsolidated rock areas (Clark et al., 1987). Borehole closure has also been verified in the routine experience of field engineers and/or petroleum consultants who encounter difficulty in keeping boreholes open while drilling and running casing and sometimes find boreholes closed when re-entry is attempted for plugging. Experience from re-entering and plugging abandoned wells near DuPont injection facilities confirmed that the boreholes are closed by natural processes in the Texas Gulf Coastal Plain (Meers, 1986 and Klotzman, 1986).

These observations explain why abandoned boreholes without production/long string casing are normally sealed by natural phenomena. Although closure of the borehole by caving sands and swelling shales would provide a significant obstacle to vertical fluid movement in the well, the approach used to model the potential for fluid movement in abandoned boreholes assumes that borehole closure will not occur. The resulting modeling calculations thus include a large safety factor.

4.5   Drilling Methods and the Mud Column

The artificial penetrations were classified by their drilling methods (rotary vs. cable). Because boreholes tend to close in unconsolidated rock formations such as the geologically young sands and hydrated shales of the Gulf Coastal Plain, rotary drilling has been the preferred drilling method. Generally, drilling mud is carefully balanced to keep caving sands and sloughing shales from entering the borehole. Rotary drilled dry holes without plugging records can be assumed to have been left mud-filled as a minimum condition because there is no economic reason to recover the drilling mud prior to

abandonment (Johnston et al., 1986). An exception to this is with modern day drilling fluid techniques, which can use polymer base or oil-based muds which are both economic to recover and extract from the borewell; however, the hole during extraction is typically filled with a less expensive bentonite mud. Mud characteristics (density, viscosity, type, and pH) were obtained from geophysical well logs, state, and operator records when available.

Rotary drilled dry holes with protection and/or production casing strings were reviewed for perforations because a well that has been production tested by perforating usually has the drilling mud replaced with a water cushion.

Mud plugs provide an effective barrier to vertical fluid flow in the abandoned wellbore. The permeability of the mud plug is less than that of the surrounding sand formations which, in combination with the hydrostatic head of an overbalanced mud column that is sufficient to counterbalance increased formation pressure due to injection, creates an effective barrier to vertical fluid flow. These factors, combined with borehole closure, minimize the chance of encountering a truly open conduit in an artificial penetration that was drilled in unconsolidated regions.

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5.0   EVALUATION METHODOLOGY FOR NON-ENDANGERMENT

5.1   Plugging

The "Statewide Rules For Oil, Gas, and Geothermal Operations" (Railroad Commission of Texas, 1986), from the State of Texas establish very stringent plugging requirements for abandoned wells. The Texas Railroad Commission, under Statewide Rule 14 (1967), demands all formations bearing USDWs, oil, gas, or geothermal resources be protected with typespecific cement plugs and mudladen fluid. Uncemented areas in the abandoned wellbore must be filled with a mudladen fluid weighing at least 9.5 lb/gal (Railroad Commission of Texas, 1986). Due to the site specific geologic conditions present at Spindletop Dome, higher mud weights of at least 10.1 lb/gal are required in order to drill to the Frio Sand interval.

Setting depths for cement plugs are dependent upon the construction of the well and the geologic environment. Wells abandoned with only surface casing should be plugged across the base of the lowermost Underground Source of Drinking Water (USDW) regardless of casing depth. When insufficient surface casing is set to protect all USDWs and such strata are exposed to the open wellbore, a cement plug must be placed across the exposed strata with an additional cement plug set across the surface casing shoe (Railroad Commission of Texas, 1986). When sufficient surface casing has been set to protect all USDWs, a cement plug must be set across the surface casing shoe (Railroad Commission of Texas, 1986).

For wells abandoned with protection and/or production casing that have been cemented through all underground sources of drinking water strata, all productive horizons must have cement plugs placed inside the casing and cement plugs centered opposite the base of the lowermost USDW (Railroad Commission of Texas, 1986). For wells abandoned with protection and/or production casing set back to surface, the casing must be perforated at the depths required to protect all productive horizons and the lowermost USDW with cement placed outside of the casing by squeeze cementing (Railroad Commission of Texas, 1986).

Wells plugged in accordance with these stringent cement requirements obviously do not have the potential to provide pathways for the injection-induced movement of fluids into

a USDW, and were not evaluated further for purposes of demonstrating compliance with the "Non-Endangerment" standard.

5.2   Wells Requiring Additional Evaluation

Wells that were not properly plugged with cement were evaluated further to determine if they required additional evaluation through modeling. These wells can be categorized as follows:

1   those wells that are not deep enough to penetrate the Frio Injection Interval; or

2   those wells that are geologically separated by sealing fault(s) or stratigraphy (Frio Sand truncation) from the active injection interval.

This category of wells therefore does not need to be evaluated further. These additional evaluation sub-criteria are discussed in the following subsections.

5.2.1   Well Depth

Artificial Penetrations that are not deep enough to penetrate the Frio Injection Interval Sand can not provide a conduit for fluid movement and therefore do not require further evaluation. These wells are considered safe as abandoned for the Frio Injection Interval Sand.

5.2.2   Truncated Frio Injection Interval Sand

Artificial Penetrations drilled deep enough to penetrate the Frio Injection Interval Sand and located along the periphery of Spindletop Dome, west of the truncation point of the Frio Injection Interval Sand can not provide a conduit for fluid movement due to the fact that there is no Frio Sand is present. Since no pressure communication exists with the active injection interval, therefore, these wells do not require further evaluation and are considered safe as abandoned for the Frio Injection Interval Sand.

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5.2.3   Well Location With Respect to Fault A

Artificial Penetrations that are deep enough to penetrate the Frio Injection Interval Sand and located south of Fault A, can not provide a conduit for fluid movement since the fault is sealed, and no pressure communication exists with the active injection interval. Therefore, these wells do not require further evaluation and are safe as abandoned for the Frio Injection Interval Sand.

5.2.4   Well Construction

For the purpose of this protocol, a properly constructed well is defined as a well in which the annulus between the borehole and a casing string has been effectively sealed by cement across and/or above the correlated injection interval(s), thereby preventing vertical fluid movement. Wells that were drilled into or through the injection interval and abandoned with protection and/or production casing left in the hole could potentially provide a pathway for fluid movement. If cement was not circulated to a depth above the correlated injection interval, only drilling fluid would provide the same resistance to vertical fluid movement as a mud plug in the wellbore.

5.3   Incomplete Records

Most of the data on the artificial penetrations in the Area of Review were obtained from state records kept on file at each specific state agency. Other records could be obtained from operators and companies. Wells that were spotted on Texas Railroad Commission Oil Field maps, or identified as having been drilled, were documented as being adequately plugged. In the event documentation is not complete, or inconclusive, these wells were then evaluated or modeled for possible vertical fluid movement utilizing the known data. In the event documentation is not present, a negative certification letter is provided by the Texas Railroad Commission documenting and reviewing all available records from 1919, indicating that no record of forms exist. This was the case with Artificial Penetration No. 331 where the Railroad Commission found no well records in their files, and a negative certification letter was then issued.

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6.0 EVALUATION METHODOLOGY FOR NO-MIGRATION

6.1 10,000 Year Plume Contact

Artificial penetrations that penetrate the injection interval and are located within either the present day plume area, or the area across which the injectate plume is projected to move during a 10,000year period, were evaluated for possible fluid constituent migration out of the injection zone. Artificial penetrations located outside either the conservatively modeled present day plume area, or the area outside which the injectate plume is conservatively projected to move in 10,000 years, were not evaluated because they can not serve as potential vertical conduits for molecular diffusion or migration of fluid out of the injection zone.

6.2 Proper Plugging

Wells abandoned with only surface casing in the hole should be plugged above the Frio Injection Interval Sand within the injection zone. Wells abandoned with protection and/or production casing across the injection zone are considered safe per the nomigration criteria if the following conditions are present: 1) Primary cementing--the casing has been cemented through the injection zone, or 2) Secondary cementing--the casing has been perforated and cement placed outside the casing by squeeze cementing above the Frio Injection Interval. Both conditions must be present within the injection zone or across the top of the injection zone. Wells not plugged in accordance with the above criteria were evaluated or modeled for potential upward molecular diffusion of injected constituents out of the injection zone.

6.3 Active Wells

Active wells, including shut-in wells, can be considered safe since they will be plugged according to state regulations upon abandonment. For purposes of this protocol, a properly constructed active well is defined as a well in which the annulus between the borehole and a casing string has been effectively sealed by cement across and/or above the correlated injection zone, thereby preventing vertical fluid movement. Active artificial penetrations not constructed in accordance with the above criteria were evaluated or modeled for potential upward fluid movement of constituents out of the

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injection zone. Texas Railroad Commission and Texas Natural Resource Conservation Commission (TNRCC) personnel typically follow-up on the status of active (producing) wells especially if there is an annual status changes.

6.4   Incomplete Records

Most of the data on the artificial penetrations in the Area of Review were obtained from state records kept on file at each specific state agency. Other records could be obtained from operators and companies. Wells that were spotted on Texas Railroad Commission Oil Field maps, or identified as having been drilled, were documented as being adequately plugged. In the event documentation is not complete, or inconclusive, these wells were then evaluated or modeled for possible vertical fluid movement utilizing the known data.   In the event documentation is not present, a negative certification letter is provided by the Texas Railroad Commission documenting and reviewing all available records from 1919, indicating that no record of forms exist.   This was the case with Artificial Penetration No. 331 where the Railroad Commission found no well records in their files, and a negative certification letter was then issued.

6.5   Offset or Other Disposal Operations

If injection wells (waste disposal, saltwater disposal, enhanced recovery, or other) were found in or near the Area of Review, operation and completion records were obtained for those wells. Injection intervals and volumes injected were researched and subsequently modeled to show if significant pressure increases resulted from the additional injection source(s).

6.6   Data Organization

After collecting the information from the various data sources, a critical review of each artificial penetration was conducted. All artificial penetration records were examined to identify improperly constructed and/or plugged wells, along with other disposal operations which may exist in the Area of Review. After each data source was reviewed and pertinent data extracted, each artificial penetration was given a unique identification number. A base location map was built from all of the base maps showing each well with its identification number and its proper location.

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7.0 CORRECTIVE ACTION PLAN

Wells that do not meet Non-Endangerment and No-Migration modeling or evaluation criteria are labeled "potential problem wells" and could require possible corrective action. No corrective action plan is warranted since all wells meet the Non-Endangerment and No-Migration criteria at Beaumont Works.

Should potential problem wells be identified, and should vertical fluid movement be calculated, then the following procedure is recommended:
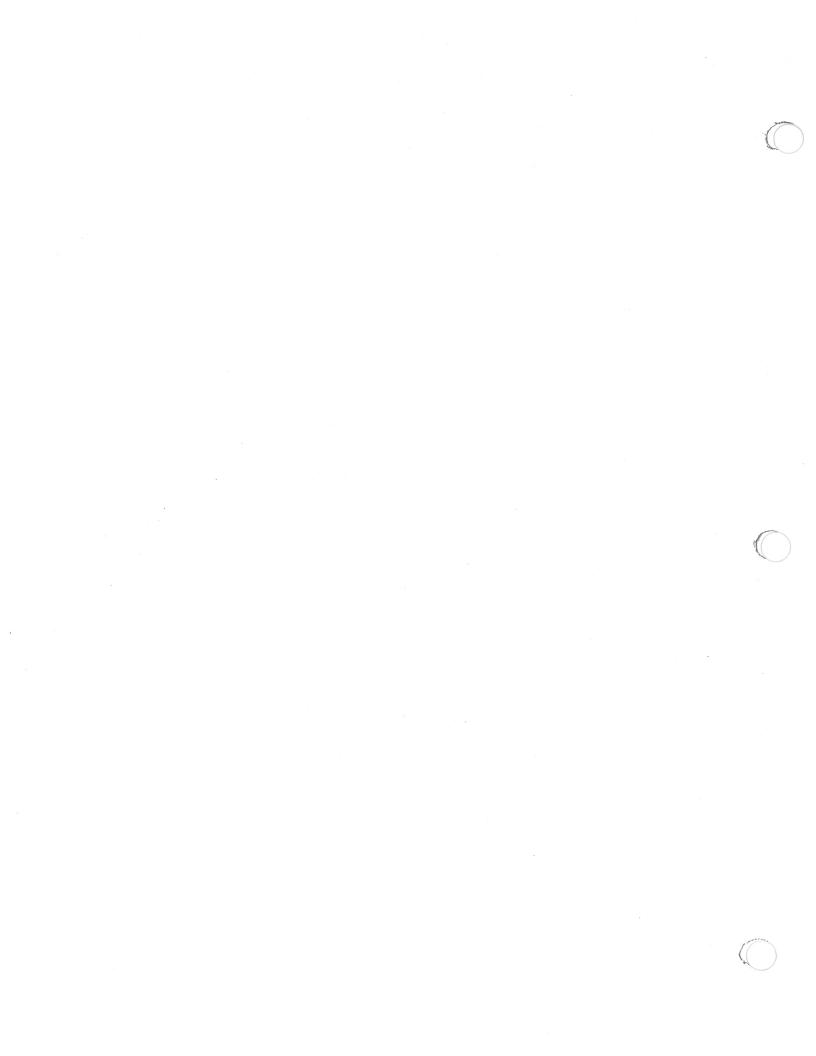
1. search for private or other offset records;

2. locate and re-enter the problem well to plug properly;

3. lower the injection rate to reduce pressure (head) driving force;

4. recomplete the injection well at a greater depth so that the potential problem well can tolerate a higher pressure without fluid movement;

5. recomplete the injection well in a reservoir deeper than the potential problem well penetrates;

6. increase the density of the injected waste to prevent vertical fluid movement.

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DuPont Beaumont Works Petition Reissuance
GeoHydroLogicPro, LLC

4-4-19

Dow Beaumont Aniline
Frio Reissuance No-Migration Petition
October 31, 2018

APPENDIX 4-5

Appendix 4-5

**The Determination of Maximum Injection Pressure for
Effluent Disposal Wells – Houston, Texas Area (Price, 1971)**

THE DETERMINATION OF MAXIMUM INJECTION PRESSURE

FOR EFFLUENT DISPOSAL WELLS -

HOUSTON, TEXAS AREA

William Henry Price

MASTER OF SCIENCE IN CIVIL ENGINEERING

THE UNIVERSITY OF TEXAS AT AUSTIN

December, 1971

PREFACE

It is with a great deal of satisfaction that I present this paper, not only as an academic requirement, but hopefully as a helpful contribution to some of the current industry problems. As might be expected, the pleasure derived in achieving a solution to such a large engineering problem was preceded at times with a feeling of considerable perplexity and frustration. However, I feel that the cost of this study, in terms of the time and money expended, will be justified by its usefulness both to me and to industry. As this study proceeded, I became aware of the major contribution of our universities and particularly The University of Texas, in providing the technical background and tools necessary for this type of research. A good example is the availability of the computer facilities at the University on which more than 300 computer runs were made in the perfection of the calculation technique shown here.

All of the questions attached to "The Determination of Maximum Injection Pressure for Effluent Disposal Wells, Houston, Texas Area" have not been answered. But I feel that a good beginning has been made. The method of images has been utilized in conjunction with the Theis non-equilibrium equation in the solution of non-steady state flow conditions. This method was used because I felt it could best be adapted by most of the technicians involved in this work. It would be interesting to compare this solution to the reservoir modeling technique recently illustrated by Van Pollen and Bixel (Reservoir Modeling (9), Oil and Gas Journal, May 11, 1970 and Reservoir Modeling (10), Oil and Gas Journal, June 29, 1970). This technique involves a use of the fundamental flow equations and the

equation of continuity as the solution tools. The "reservoir" simulation
is effected by use of a grid system. Other investigators have used the
electrical analog model in exploring this type of problem. A comparison
of each of these methods as to accuracy and adaptability should be made.

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PURPOSE OF INVESTIGATION

Much concern has been expressed in the recent past concerning the problems which have arisen or which may arise as a result of subsurface disposal of liquid wastes in the industrial areas of our country. Included in this expression of concern has been a wide range of commentary ranging from the arm-waving declarations of the uninformed citizen to the knowledgeable treatment and discussion of the problem, such as that submitted in the Geological Survey Circular #C-631 by Arthur M. Piper (10). Piper discusses some of the current unsolved problems and effectively places the technique of subsurface disposal in its proper perspective.

Many questions have arisen with the advent of waste disposal in the subsurface such as -- Will this waste eventually migrate to outcrop areas? How much waste input capacity is available in the subsurface formations? Are subsurface formations capable of withstanding the increased pressure effects due to injection? and, Will the liquid waste under the pressure and temperature conditions in the zone of disposal change in chemical character or deteriorate due to adsorption or chemical recombination?

Some of the problems which may arise from the conduct of unsupervised subsurface disposal are:

(1) Updip encroachment of liquid wastes into fresh water horizons;

(2) Fracturing of adjacent formations and migration of the liquid waste outside the zone of intended confinement;

(3) Creation of excessive reservoir pressure such that earthquake effects are created.

A complete investigation of all of these phenomena is impossible in a single study such as this, but a beginning investigation has been made and is presented here. The most frequent question raised when considering the process of subsurface waste disposal is the question of what pressure effects are created and what alteration of existing hydrodynamic gradients takes place in the zone of disposal? It is well known that the injected waste effectively displaces the original connate water in the area of the injection well but the magnitude or extent of the pressure effect thus created has been investigated by very few. The primary purpose here was to make computations defining the pressure capacity for subsurface disposal in the Upper Frio and Lower Miocene horizons of the Houston industrial area. The term "pressure capacity" in this case is defined as that capacity, in terms of reservoir pressure increase, to which these zones may be subjected and the corresponding injection volumes which may be disposed upon reaching this pressure limitation. It is desirable to know too, that if excessive injection pressures are anticipated or created, then what injection procedures should be formulated to avoid such a pressure buildup.

The possibility of pressure parting along old fault planes due to pressure buildup is not treated separately here since the magnitude of pressures created by injection are not sufficient to overcome existing earth forces. Sheets and Weaver (12, 19) report on the existence of active surface faulting in the Houston area, but no injection well has been permitted within proximity of such faulting. An area map, Figure 1,

shows the general location of the known surface faults together with a contour map on the base of the fresh water interface in the Houston-Galveston area (20).

Computations on the injection-pressure capacity of a Miocene interval in the Houston area were made where data for interpretation is available and where major injection programs will possibly take place. The Houston industrial area in this paper is described as that area extending from the City of Houston, Inc. and the Houston ship channel, southward through the Texas City industrial area to Galveston, covering portions of both Galveston and Harris counties. During the last 10 years there have been 25 permits granted for disposal and 12 industrial disposal wells completed in this area. Figure 2 shows the location of these injector permits and Figure 3 shows the permitted injection depths together with the completed injection intervals for those wells which have been constructed. Current (July, 1971) disposal volume is estimated at a rate of 2300 GPM.

The effluent disposal volume does not include that volume of produced salt water disposed from oil fields in the area into zones which are non-productive of oil and gas. This latter volume is estimated at 1400 GPM as of July, 1971. If all of the permitted industrial disposal wells had been constructed, the permissible injection volume for the area would exceed 5000 GPM. The combined current injection rate from oil field and industrial sources is 3700 GPM.
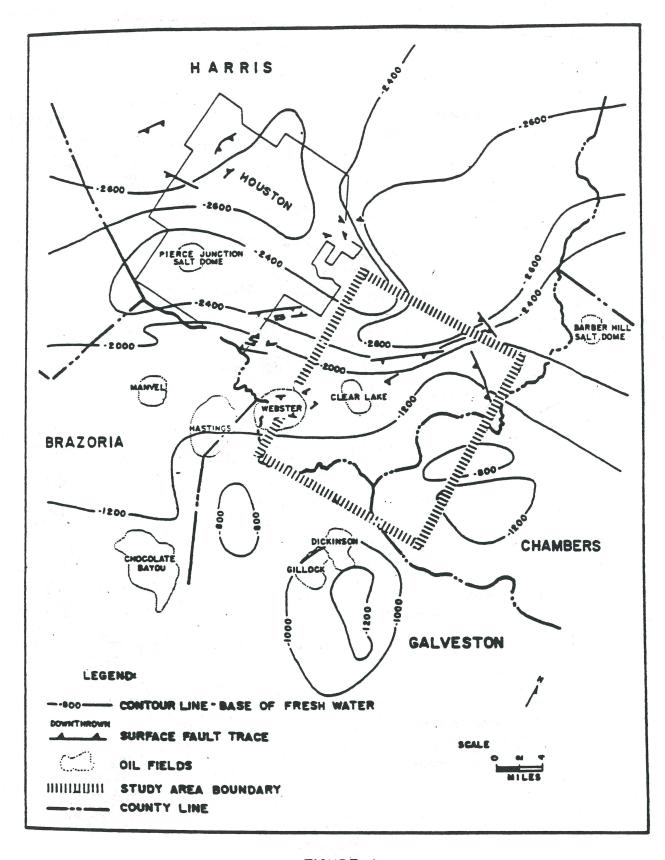
FIGURE 1

PORTION OF BRAZORIA, GALVESTON AND HARRIS COUNTIES, TEXAS
AREA MAP
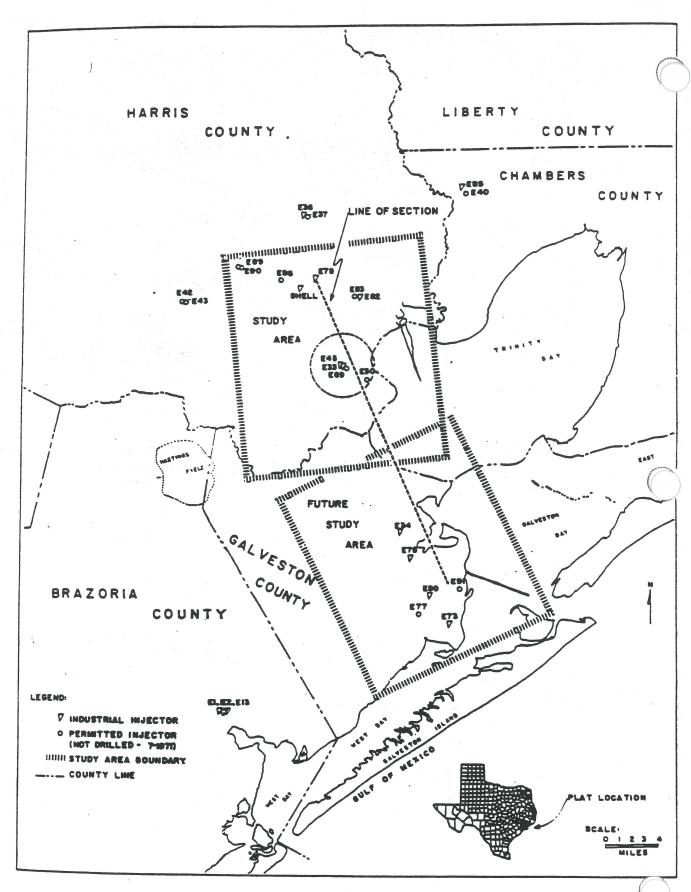
FIGURE 2

MAP OF STUDY AREAS AND INJECTOR LOCATIONS

FIGURE 3

PROFILE OF PERMITTED INJECTION INTERVALS
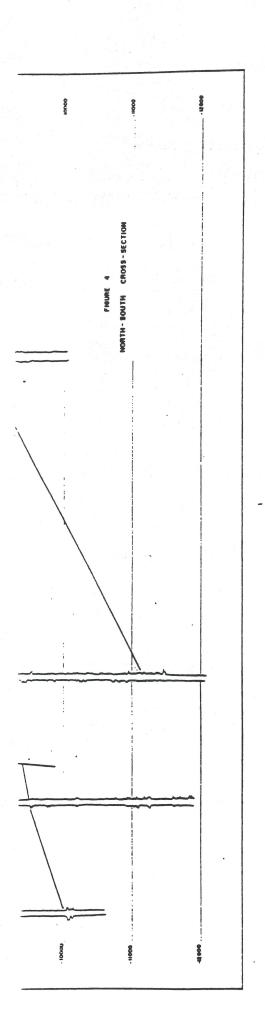
GEOLOGICAL INVESTIGATION

The first major task facing any investigator who attempts to define this problem is that of defining the container or "aquifer" into which subsurface disposal will occur. The major zones of disposal in the area are the Frio and Miocene formations of the Tertiary System. All of the sedimentary rocks have been deposited within the last 30 million years with deposition and sedimentation continuing to this time. These rocks slope gently seaward with a dip-rate of 100' per mile on the base of the Miocene formation and a dip-rate of 140' per mile on top of the Frio formation of Oligocene series. This is shown in the north-south cross-section, Figure 4. It appears from study of electric logs and published data that the sediments reach an outer limit and appear to be closed by shale deposition from direct communication with Gulf waters.

Rogers (11) explains the mode of deposition in the Marginulina-Frio series in which the sand, silts and clays have a maximum sand development with sand splitting up and going out into shale both landward and Gulfward. Down-dip the change is from a nearly solid sand section, to broken sands in the Marginulina and Upper Frio, and finally to shale with little or no sand. This phenomena is further illustrated in two study group reports published by the Houston Geological Society on the stratigraphy of the upper Gulf coast of Texas. These studies were published in 1954 and 1959 (6). Timm and Maricelli (16) describe a three-fold cycle of deposition for the Miocene series of southwest Louisiana (also southeast Texas) in which there is:

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FIGURE 4

NORTH - SOUTH CROSS-SECTION

(1) A rapid transgressive phase with deposition of a thin limey section ("transgressive" meaning landward movement of the seashore);

(2) An inundative phase slowly depositing a thicker marine shale section; and

(3) A prominent regressive phase with rapid deposition of a massive section of intertongued non—marine and marine sediments.

Others describe the regional deformation occurring during the time of deposition in which contemporary faulting with deposition and major upthrusting salt movement have broken the area into a veritable "jigsaw puzzle" of blocks which have varying degrees of communication between them. The Lower Frio horizon exhibits a greater degree of brokeness and faulting due to longer exposure to earth stresses while both the Frio and Miocene formations exhibit less brokeness with decreasing depth as they approach the Houston, Incorporated city limits.

All of these phenomena were observed as a result of a regional study and mapping, with the aid of published structural maps and electric log correlations. The pattern for the major structural features of the subsurface was obtained through the courtesy of the Geomap Co. of Houston, Texas, and the detail mapping of the structural horizons was completed with the aid of electric logs. Structural maps were prepared on the top of the Frio formation, the base of the Miocene formation, and on a marker near the top of the Miocene formation. Approximately 200 electric logs were utilized in this study which in the writer's opinion afforded ample coverage of the major structural features.

CHOICE OF STUDY AREA

A study area was selected which provided the most complete injection history available in the area. This area surrounds the Celanese Chemical Co. plant, Clear Lake, Texas, which has maintained a pressure monitor well 6,250' west of its injection operation, since they commenced injection in 1967. Because insufficient surface casing was set in the completion of oil wells in the Clear Lake Field located 10,000' west of their waste disposal wells, the monitor well has been maintained to insure against excessive pressure buildups in the vicinity of these wells. The pressure monitoring well was required as a condition in permitting the drilling and completion of effluent disposal wells E-33, E-45 and E-69. The location of these wells is shown at the center of the dashed circular area on Figure 5. The pressure monitoring well is shown to the westward, opposite the Clear Lake oil field.

The pressure monitoring well provided by the Celanese Chemical Co. is the only well of this type constructed in the area by which continuous pressure observation can be maintained. Fortunately, the presence of this well and the data from it has enabled a comparison of pressure response which otherwise would not have been possible. All of the injection data necessary to this study was obtained from records of the Texas Water Quality Board and the Railroad Commission of Texas. Electric log records were made available through the courtesy of the Houston Log Association Library.

The study area selected for pressure buildup calculation is shown in Figures 1 and 2 and extends from the Houston ship channel area

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southward approximately 18 miles with a width of 16 miles. This is an area of concentrated industrial development and by coincidence, the area overlies a series of thick Miocene and Frio sand bodies which appear quite suitable for waste disposal. Both the Miocene and Frio injection zones of the Houston industrial area can be divided into distinctive sand intervals when considering the selection of specific zones for injection. The Basal Miocene zone considered in this study is a massive sand interval of approximately 300' thickness in the study area with thickening to 500' in the Texas City area. This zone has been selected more than others for disposal purposes since it is relatively shallow in depth, 5,000' - 6,000', and has greater permeability than the deeper Frio horizon. The Miocene sand interval in the study area is separated laterally several miles from the nearest fresh water interface and the injection area permitted by the Texas Water Quality Board is further separated from the fresh water area by major regional faulting extending in an east-west direction. Along the north edge of the study area (the Houston ship channel), the Frio formation is utilized for disposal primarily because of a lesser number of well penetrations and because it too is removed laterally many miles from the nearest fresh water interface. The Miocene interval overlying the Frio thins rapidly north of the Houston ship channel and is unsuitable for injection.

After the structure and isopach maps were prepared, as shown in Figures 5 and 6, a fault block map was constructed (Figure 7) for the study area in order that the fault system could be adapted for pressure buildup calculations. The sand thickness or isopachous map was prepared by estimating the total sand thickness within each electric log which
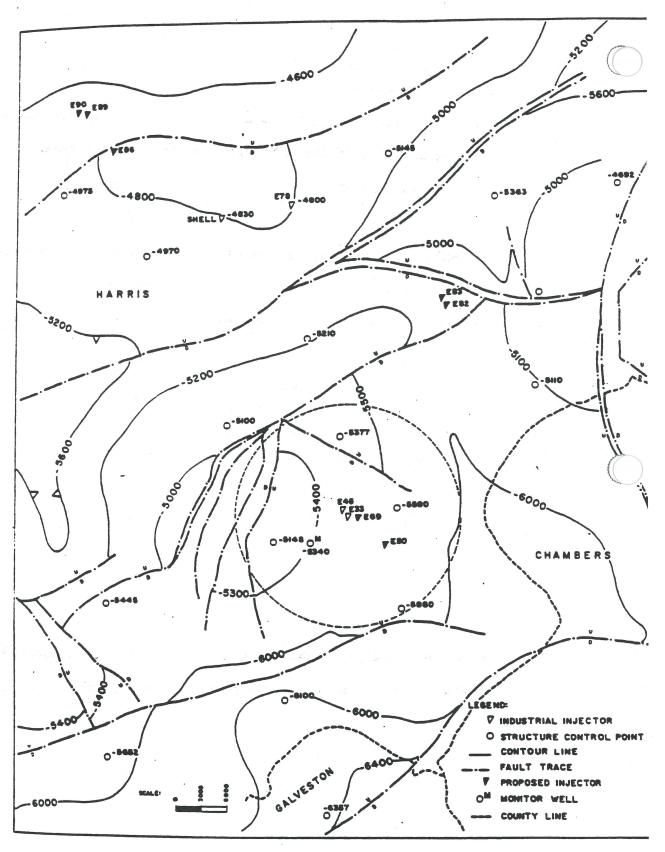
FIGURE 5

STRUCTURE MAP ON BASE OF MIOCENE
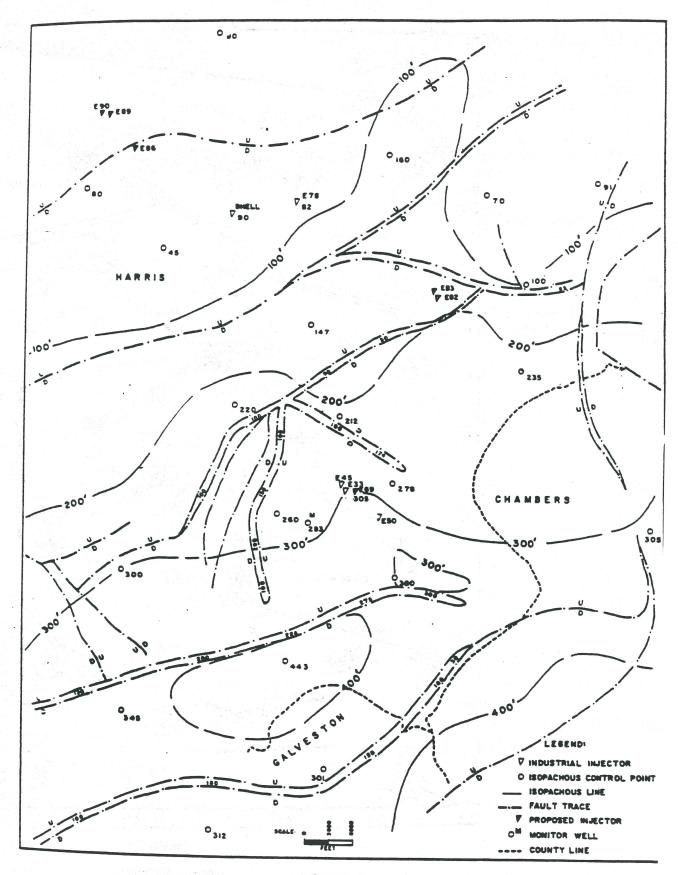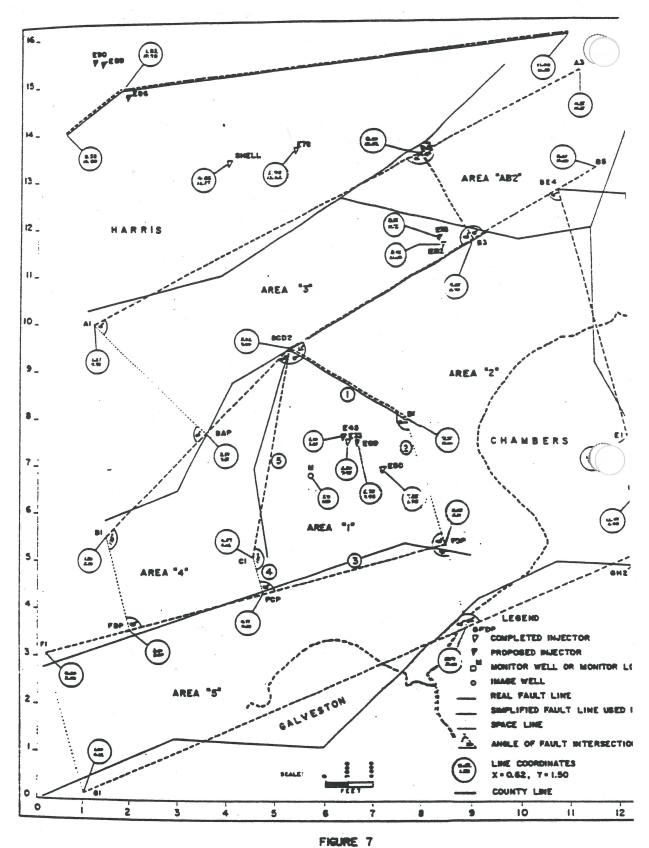
FIGURE 6

ISOPACHOUS MAP
BASAL MIOCENE

LEGEND:

▽ INDUSTRIAL INJECTOR
○ ISOPACHOUS CONTROL POINT
── ISOPACHOUS LINE
─·─· FAULT TRACE
▼ PROPOSED INJECTOR
○ᴹ MONITOR WELL
···· COUNTY LINE

FIGURE 7

FAULT BLOCK MAP

was considered to be in hydrologic communication. Any shale separation which could not be correlated over the area was not considered sufficient to prevent hydrologic communication. This procedure is demonstrated on the cross-section, Figure 4.

A future study area is shown in Figure 2 in the Texas City vicinity. Time did not permit the inclusion of this area in the pressure calculations. Similar geologic conditions would be exhibited anywhere between the Houston-Galveston limits, but variations will exist in the size of the fault blocks, the transmissibility of the sands, the areal extent of the sands, and the sand thickness.

METHOD OF CALCULATION

Mueller and Witherspoon (9) present an interesting discussion of the available methods for calculating the pressure interference effects within reservoirs and aquifers due to production or injection. The solutions of Mortada and Theis (15) are both based on the diffusivity equation as applied to the case of an infinite radial system subject to a constant terminal rate. The equation is obtained by combining the material balance equation with Darcy's flow equation. The Theis approach employs the exponential integral and is valid for pressure conditions that occur some distance away from the flow disturbance. It is derived from the concept of a point source as opposed to a flow across some finite area. The Mortada results on the other hand are valid at all points within the reservoir or aquifer. In the paper, these results are presented in terms of dimensionless ratios of the radius where the pressure is desired, to the radius where the flow rate is measured. Their main use in the past has been in aquifer studies rather than utilization in oil reservoirs.

Quoting further from Mueller and Witherspoon, the mathematical formulation of the point source solution and its resultant exponential integral are due to Lord Kelvin. Theis however is apparently the first to demonstrate how the point source solution could be employed in the analysis of a non-steady-state flow problem. In recognition of his early work, the exponential integral solution is normally referred to in the field of hydrology as the Theis solution. The variable "X" is defined in the Theis solution as a dimensionless quantity inversely related to

time. "X" is the independent variable in the Theis solution and the integral value or dependent variable is related to the dimensionless pressure drop. A comparison of the dependent and independent variables with those of Mortada and Van Everdingen and Hurst are shown in Table 1 as adapted from the Mueller and Witherspoon paper. They conclude that for all radius ratios (where $r_d = r/r_w$) greater than 20, the Theis solution adequately gives the pressure drop after any practical time. The Theis equation and the solution of the exponential integral are shown below.

$$PR = \frac{114.6\ Q}{TS} \int_u^\infty \frac{e^{-u}}{u}\ du \qquad (1)$$

$u = 1.87\ R^2 S / TS\ (T)$

PR = Drawdown or buildup, feet, at a point in the well area

Q = Recharge or discharge of the well, gallons/minute

TS = Transmissibility, gallons/day/foot

R = Distance to monitor point, feet

S = Coefficient of storage, decimal fraction

T = Time, days since injection started

$$\int_u^\infty \frac{e^{-u}}{u}\ du = W(u) = -0.577216 - \ln u + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} - \frac{u^4}{4 \cdot 4!} + - - - - \qquad (2)$$

TABLE 1

COMPARISON OF DEPENDENT AND INDEPENDENT VARIABLES, THEIS EQUATION

	Dimensionless Independent Variable	Dimensionless Dependent Variable	Dimensioned Pressure Drop
Theis	$X = \dfrac{r^2 \phi \mu c}{4kt}$	$Ei(-X)$	$\dfrac{qu}{4\pi kh} Ei(-X)$
Mortada, and van Everdingen and Hurst	$t_D = \dfrac{kt}{\phi \mu c r_w^2}$	ΔP_D	$\dfrac{q\mu}{2\pi kh} \Delta P_D$

$$t_D \text{ (Eq. 7a)} = \frac{t_D(\text{Mortada})}{r_D^2} \quad \ldots \ldots \ldots \ldots \ldots \ldots \quad (8a)$$

From the above, it can also be seen that, with reference to the Theis solution,

$$t_D(\text{Eq. 7}) = \frac{1}{4X} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad (9a)$$

and

$$\Delta P_D = \frac{Ei(-X)}{2} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad (10a)$$

Pressure buildup due to injection at variable rates was then computed as:

$$PR = \frac{114.6}{TS} \left[Q_1 W(u)_1 + \Delta Q_2 W(u)_2 \; \text{---} \; + \Delta Q_n W(u)_n \right]$$

(3)

where:

ΔQ_2 = Change in injection rate from Time 1 to Time 2.

$$u_1 = \frac{1.87 \, R^2 S}{TS(T)}$$

$$u_2 = \frac{1.87 \, R^2 S}{TS(T-T_2)}$$

T_2 = Duration (days) from beginning of injection to the time when the second injection rate began.

Ferris (3) gives an excellent discussion of the solution of aquifer problems utilizing the method of images and the Theis solution. A complete solution of the method would not be practical without computer usage, but nevertheless the method of images is the only tool by which approximations of pressure buildup or drawdown can be made relatively quickly utilizing only a slide rule or desk calculator. This method has been adapted for the solution of pressure buildup due to waste disposal in the Houston area.

Each fault block was described by inputting the coordinates for a closed polygon with a numbering system which describes those fault lines, or space lines, common one to the other. Since the fault lines represent barriers to fluid flow, imaginary wells or "images" are

utilized across the fault and opposite from the real injector to duplicate hydraulically the effects on the flow pattern caused by the physical barrier. Ferris (3) explains that "the finite flow system is thereby transformed by substitution into one involving an aquifer of infinite areal extent in which several real and imaginary wells can be studied by means of the formulas already given. Such substitution often results in simplifying the problem of analysis to one of adding effects of imaginary and real hydraulic systems in an infinite aquifer."

To facilitate usage of the method of images, fault lines having dog legs and curvature were simulated by averaging with straight lines such that intersecting fault angles of more than 90° would not have to be considered. The method of images requires the placement of image wells such that a symmetrical pattern is created with no image wells appearing inside the fault wedge desired for pressure calculation. This limitation restricts consideration of fault angles to those angles which when divided into 360° yield a quotient which is an integer number. Although in some instances this requirement causes a slight error in the magnitude of calculated pressure buildup values, its effectiveness is not diminished in a fault system containing several fault wedges since the errors become compensating. Figure 8 shows a real injector inside a fault wedge whose angle is 69.1°. Division of this angle into 360° indicates that 4.2 image wells would be required to balance the pressure buildup caused by injection into the real well. This is impossible to construct and four image wells are located as shown. The calculation inside a fault wedge of 90° would require the use of four wells with three image wells located outside the angle in balancing the one real well

u = 69.1
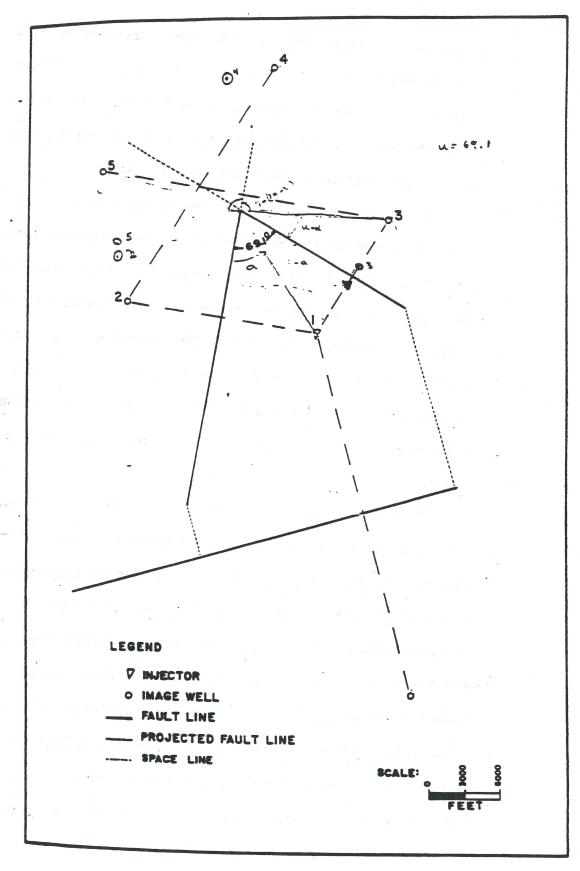
FIGURE 8

IMAGE WELL CONSTRUCTION

inside the angle. A fault wedge of 80° would require 3-1/2 image wells, plus the real well (which is impossible to construct). The nearest integer angle of 72°, yielding four image wells plus the real well, must be utilized. Wherever the quotient was a fractional number, the number of image wells was selected as the nearest whole number.

The basic method of buildup calculation was carried out by fault block areas where the pressure effect of injection into each area was determined. Figure 7 shows the adaptation of the fault lines and the space lines in comparison with the real fault outline. Coordinates of each line intersection are shown. The increase in piezometric head at each monitor point was accumulated from the effect of injection by each real well and each of its image wells in the fault block system. An example computer printout of each successive step for an image well is shown as Table 2.

Each line of the fault block polygon was subdivided into 500' increments, and the pressure buildup determined at each of these points. The weighted average buildup, PRBAR, was determined for each line and its center of gravity located along the line, after which the radial distance from this point to the real injector was determined. To determine the outflow from each fault line (where space lines existed, or where the faults are leaking), an "FL" factor was calculated for each line which was directly proportional to the transmissibility across the fault, TB, the pressure buildup, PRBAR, and inversely proportional to the well function, W(u), from the Theis equation. A summation of these factors for each line, SUMM (NP), and for all required lines around the polygon, SUMFLT, yields the "F" factor or outflow factor,

TABLE 2
PRESSURE BUILDUP CALCULATIONS
INCREMENTAL TIME STEPS

| Change in Piezometric Head + Ft. - | Incremental Time, Days | Sum of PR, Ft. | Number of Well Image Real Monitor | | | | Rate of Recharge (+) Discharge (-) GPM | |

AA= 1554.811   AP= 9224.105   NP= 6   ANGLE=-80.298   JJ= 1
A= 5.860 MS   ZK= -1   NP= 6

PR= 1.145	T= 3650.000	SUM= 39.209	K3=11	J= 3	JJ= 1	JD= 1	QD= 20.127	TS= 6000.0
PR= -.553	T= 3285.000	SUM= 38.656	K3=11	J= 3	JJ= 1	JD= 1	QD= -10.063	TS= 6000.0
PR= 0.000	T= 2920.000	SUM= 38.656	K3=11	J= 3	JJ= 1	JD= 1	QD= 0.000	TS= 6000.0
PR= 0.000	T= 2555.000	SUM= 38.656	K3=11	J= 3	JJ= 1	JD= 1	QD= 0.000	TS= 6000.0
PR= 1.615	T= 2190.000	SUM= 40.272	K3=11	J= 3	JJ= 1	JD= 1	QD= 33.993	TS= 6000.0
PR= .015	T= 1825.000	SUM= 40.287	K3=11	J= 3	JJ= 1	JD= 1	QD= .341	TS= 6000.0
PR= .007	T= 1460.000	SUM= 40.294	K3=11	J= 3	JJ= 1	JD= 1	QD= .174	TS= 6000.0
PR= .003	T= 1095.000	SUM= 40.297	K3=11	J= 3	JJ= 1	JD= 1	QD= .088	TS= 6000.0
PR= .001	T= 730.000	SUM= 40.298	K3=11	J= 3	JJ= 1	JD= 1	QD= .045	TS= 6000.0
PR= .000	T= 365.000	SUM= 40.299	K3=11	J= 3	JJ= 1	JD= 1	QD= .023	TS= 6000.0

L=11N=10

PR= .474	T= 3650.000	SUM= 15.320	K3=11	J= 3	JJ= 1	JD= 2	QD= 20.127	TS= 6000.0
PR= -.418	T= 3285.000	SUM= 14.902	K3=11	J= 3	JJ= 1	JD= 2	QD= -10.063	TS= 6000.0
PR= 0.000	T= 2920.000	SUM= 14.902	K3=11	J= 3	JJ= 1	JD= 2	QD= 0.000	TS= 6000.0
PR= 0.000	T= 2555.000	SUM= 14.902	K3=11	J= 3	JJ= 1	JD= 2	QD= 0.000	TS= 6000.0
PR= 1.170	T= 2190.000	SUM= 16.072	K3=11	J= 3	JJ= 1	JD= 2	QD= 33.993	TS= 6000.0
PR= .011	T= 1825.000	SUM= 16.083	K3=11	J= 3	JJ= 1	JD= 2	QD= .341	TS= 6000.0
PR= .005	T= 1460.000	SUM= 16.088	K3=11	J= 3	JJ= 1	JD= 2	QD= .174	TS= 6000.0
PR= .002	T= 1095.000	SUM= 16.090	K3=11	J= 3	JJ= 1	JD= 2	QD= .088	TS= 6000.0
PR= .001	T= 730.000	SUM= 16.090	K3=11	J= 3	JJ= 1	JD= 2	QD= .045	TS= 6000.0
PR= .000	T= 365.000	SUM= 16.091	K3=11	J= 3	JJ= 1	JD= 2	QD= .023	TS= 6000.0

L=11N=10

PR= .043	T= 3650.000	SUM= 19.644	K3=11	J= 3	JJ= 1	JD= 3	QD= 20.127	TS= 6000.0
PR= -.452	T= 3285.000	SUM= 19.191	K3=11	J= 3	JJ= 1	JD= 3	QD= -10.063	TS= 6000.0
PR= 0.000	T= 2920.000	SUM= 19.191	K3=11	J= 3	JJ= 1	JD= 3	QD= 0.000	TS= 6000.0
PR= 0.000	T= 2555.000	SUM= 19.191	K3=11	J= 3	JJ= 1	JD= 3	QD= 0.000	TS= 6000.0
PR= 1.283	T= 2190.000	SUM= 20.474	K3=11	J= 3	JJ= 1	JD= 3	QD= 33.993	TS= 6000.0
PR= .012	T= 1825.000	SUM= 20.486	K3=11	J= 3	JJ= 1	JD= 3	QD= .341	TS= 6000.0
PR= .005	T= 1460.000	SUM= 20.491	K3=11	J= 3	JJ= 1	JD= 3	QD= .174	TS= 6000.0
PR= .002	T= 1095.000	SUM= 20.493	K3=11	J= 3	JJ= 1	JD= 3	QD= .088	TS= 6000.0

DEFINITION OF TERMS

PR - Incremental increase (or decrease) in piezometric head from real or image well, feet
T - Number of days since injection began to time of pressure determination
SUM - Algebraic sum of PR values at each monitor point location, JD
K3 - Counter for elapsed time period, days
J - Image well number
JJ - Number of real injector
JD - Monitor point number
QD - Incremental difference in rate of recharge or discharge, gpm
TS - Average transmissibility of sand in fault block, gallons/day/foot

$$FL = TR \times PRBAR/W(u) \tag{4}$$

$$SUMM(NP) = \sum FL \tag{5}$$

$$F = SUMM(NP)/SUMFLT \tag{6}$$

The "F" factor represents that fraction of the total fluid outflow from the fault block which will pass through any individual line. A summation of the "F" factors for any individual block would equal 1.0 or unity.

Figure 9 illustrates the procedure by which the pressure build-up is calculated at a monitor point outside a fault block where injection is occurring. Fault Line 1 of Figure 9 is assumed in this illustration to be a leaking fault through which fluid is transmitted from Fault Block 2 into Fault Block 1. Flow distribution lines are shown extending from Injectors 2 and 3 in Fault Block 2 through Line 1 and thence to the two desired monitor points JD-1 and JD-2. The determination of the outflow factor "F" across Line 1 was discussed above and the cumulative outflow volume "QA" is determined as:

$$QA = F \times QT \tag{7}$$

where QT is the cumulative total injection into Fault Block 2 at the time the pressure determination is desired.

A fractional pressure value, RATIO, was determined for each of the points 1-8 on Line 1:

$$RATIO(2) = \sum PS(2)/\sum PR \tag{8}$$

where PS(2) equals the total pressure buildup at Point 2 due to
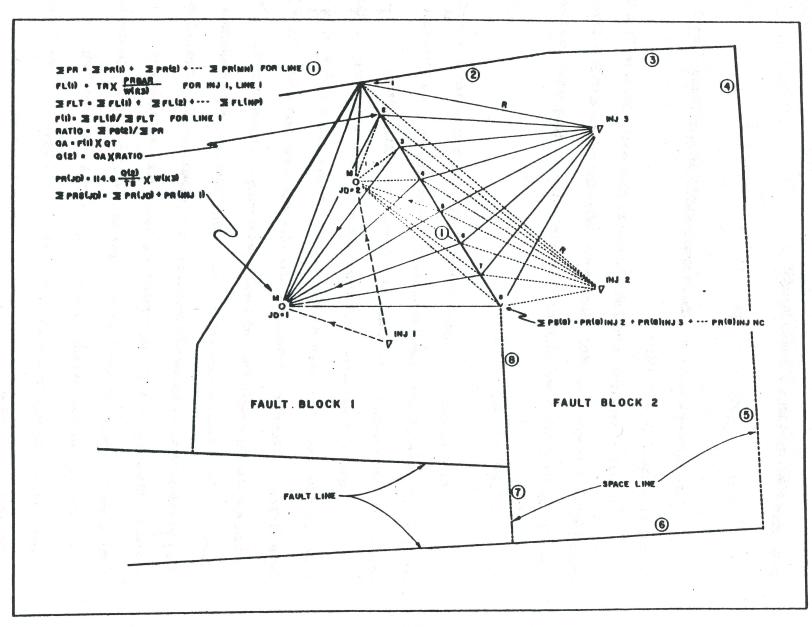
FIGURE 9

CALCULATION OF PRESSURE BUILDUP FROM AN
ADJACENT FAULT BLOCK

injection from Injectors 2 and 3, and:

$$\Sigma PR = \Sigma PS\ (1) + \Sigma PS\ (2)\ ---\ +\ \Sigma PS\ (8) \tag{9}$$

Summation of all the fractional RATIO values along Line 1 would, of course, equal 1.0 or unity.

Having determined the RATIO values for each image well point along Line 1 (located at 500' intervals) and the total outflow through Line 1, QA, the individual injection rate for each image injector was:

$$Q(2) = QA \times RATIO\ (2) \tag{10}$$

The pressure buildup at each monitor point 1 and 2 was then determined by use of the Theis equation by summation of the pressure buildup effect from each of the imaginary injectors along Line 1.

Use of the method of images in calculating pressure buildup or pressure drawdown has been previously made where the fault system was considered as completely sealing (non-leaking) and extending in an infinite direction away from the real producing or injecting well (references 3, 17). Since neither of these conditions is often encountered, corrective procedures were formulated to accommodate the actual conditions. Ideally, a real well inside a fault wedge extending to an infinite length would be balanced by image wells of equal injection volume. But injected fluids through an injector located near the end of a fault would bypass around the fault since this is the path of least pressure resistance. An image well placed opposite this injector would not have an equal injection volume due to the bypassing of fluids. Thus where the end of a fault was known, as it intersected a space line, the

injection volume for an image well outside the fault wedge was reduced by a factor, RI. This procedure is illustrated in Figure 10, where the end of a fault extending from the upper left is shown at Point A. By observing the location of the injector wells in sequential order, one can see that the image reduction factor, RI, diminishes to a very small number as the real injector is located further from the open end of the fault wedge. Line 2 is a space line connecting the two nearest points of the fault lines which define the fault block. The location of a real injector with respect to the space line determines the individual fault block in which imaging of the real well will be considered. Inside the fault wedge, the RI factor is calculated as:

$$RI = 1 - \frac{[AP(1)]^2}{[AP(2)]^2} \tag{11}$$

A real injector located past the end of a fault line is offset by an image well whose reduction factor is calculated as:

$$RI = \frac{[AP(2)]^2}{[AP(1)]^2} \tag{12}$$

as shown in Figure 10. A real injector located inside the spotted triangular area is balanced by an image well whose reduction factor is 0.5. As the RI value becomes very small, the injection rate for an image well is necessarily reduced to zero for all practical purposes. This would occur in the case of an injector in a continuous and infinite sand.
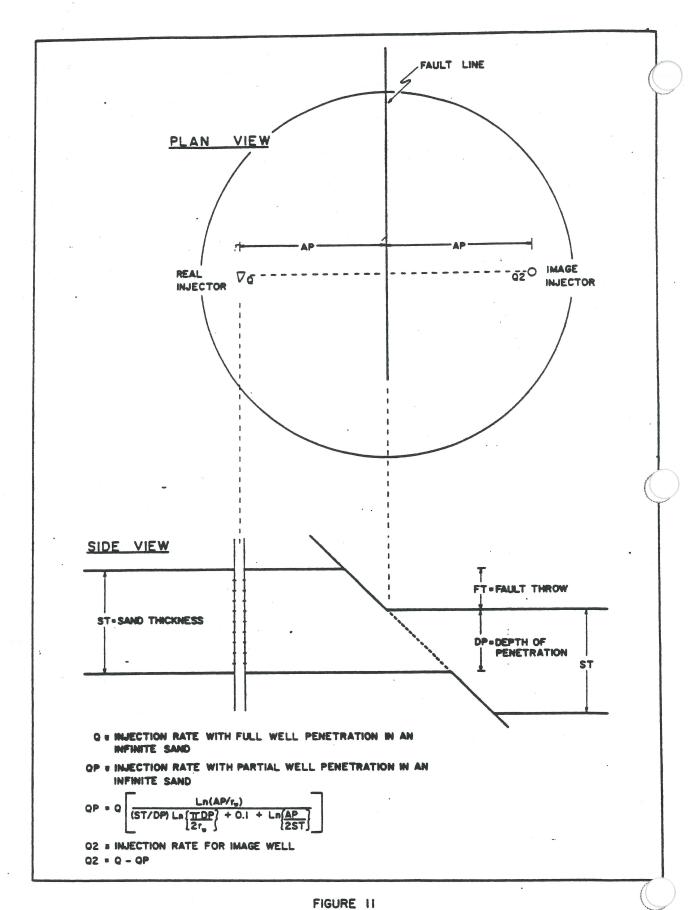
The computer program was set up so as to consider any fault line as either leaking or sealing. The leaky fault was simulated by

FIGURE D

DETERMINATION OF IMAGE WELL
REDUCTION FACTOR, RI

considering the transmissibility across the fault as being proportional
to the net sand thickness remaining in juxtaposition across the fault
plane after faulting occurred. Thus a 500' sand interval which is bi-
sected by a fault having 300' of throw, would have 200' of net sand re-
maining in juxtaposition. A similar effect is created by placing a
"partially penetrating" image well, Q2, opposite to and equidistant from
the fault line of an otherwise fully penetrating injection well as shown
in Figure 11. An image well with an injection rate equal to the differ-
ence between the fully penetrating well, Q, and a partially penetrating
well, QP (at the same location), was placed opposite the real injector
equidistant to the fault line. Where a fault wedge was considered with
each leg having a different leak rate, then the image wells were calcu-
lated alternately across each line until the full number of image wells
was satisfied. The formula for determining the injector rate through a
partially penetrating well was adopted from Todd, Page 107 (17).

A convergence procedure was formulated for computer use, such
that input data (fault leakage and transmissibility) could be varied
until the calculated transmissibility and fault leakage rate created the
desired pressure buildup at a given monitor point. Each fault block must
be hand-tailored so as to avoid repetitious calculation of the image
wells and to instruct the computer as to whether or not the fault line
was considered as terminal or infinite. Typical RI values and QP values
are shown on the printout Table 3. These calculations are from Fault
Block 2.

FAULT LINE

PLAN VIEW

|← AP →|← AP →|

REAL
INJECTOR   ▽ Q - - - - - - - - - - - - - - Q2○   IMAGE
                                                  INJECTOR

SIDE VIEW

ST = SAND THICKNESS

FT = FAULT THROW

DP = DEPTH OF
      PENETRATION

ST

Q = INJECTION RATE WITH FULL WELL PENETRATION IN AN
    INFINITE SAND

QP = INJECTION RATE WITH PARTIAL WELL PENETRATION IN AN
     INFINITE SAND

$$QP = Q \left[\frac{Ln(AP/r_w)}{(ST/DP) \, Ln\left(\frac{\pi DP}{2r_w}\right) + 0.1 + Ln\left(\frac{AP}{2ST}\right)} \right]$$

Q2 = INJECTION RATE FOR IMAGE WELL

Q2 = Q - QP

FIGURE 11

DETERMINATION OF FAULT LEAKAGE RATE

TABLE 3

CALCULATION OF FAULT FACTORS

```
HI= .500   NP= 4   JJ= 2   N= 6

HI=1.000   NP= 4   JJ= 2   N= 6
    CC=   170.699   JJ= 2   CT=    444.221

HFP=   184.921   JI= 1   JJ= 2   KJ= 4
UF=   0.000     CP=   0.0     ST=225.0     FT=225.0     TR=   0.0     NP= 4
UF=  57.91H     CP=  70.0     ST=200.0     FT=130.0     TR=1120.0     NP= 5
ANGLEF=   .27
AF=      2.91
ANGLEF=-7.67
AF=      4.H23

HI=1.000   NP= 6   JJ= 2   N= 5

HI= .500   NP= 6   JJ= 2   N= 5
UF=  57.946     CP=  70.0     ST=200.0     FT=130.0     TR=1120.0     NP= 6
UF=   0.000     CP=-280.0     ST=225.0     FT=500.0     TR=   0.0     NP= 7
ANGLEF=  84.72
AF=      2.986

HI= .674   NP= 9   JJ= 2   N= 4

HI=1.000   NP= 9   JJ= 2   N= 4
UP=   0.000     CP= -75.0     ST=325.0     FT=400.0     TR=   0.0     NP= 9
UP=   0.000     CP= -50.0     ST=350.0     FT=400.0     TR=   0.0     NP=10
ANGLEF=-61.27
AF=      5.014

HI= .500   LP= 4   JJ= 3   N= 6

HI=1.000   LP= 4   JJ= 3   N= 6
    CC=    53.611   JJ= 3   CT=    447.833
UF=   0.000     CP=   0.0     ST=225.0     FT=225.0     TR=   0.0     NP= 4
UF=  58.403     CP=  73.0     ST=200.0     FT=130.0     TR=1120.0     NP= 5
ANGLEF=   .27
AF=      2.91
ANGLEF=-7.67
AF=      4.823

HI=1.000   NP= 6   JJ= 3   N= 5

HI= .500   NP= 6   JJ= 3   N= 5
UP=  58.485     CP=  70.0     ST=200.0     FT=130.0     TR=1120.0     NP= 6
UP=   0.000     CP=-280.0     ST=225.0     FT=500.0     TR=   0.0     NP= 7
ANGLEF=  84.72
AF=      2.986

HI= .604   NP= 9   JJ= 3   N= 4

HI=1.000   NP= 9   JJ= 3   N= 4
UP=   0.000     NP= -75.0     ST=325.0     FT=400.0     TR=   0.0     NP= 9
```

DEFINITION OF TERMS

RI – Image well reduction factor

QP – Injection rate of partial penetrating well, gpm

NP – Fault line number

JJ – Number of real injector

N – Total number of calculated image wells plus real well for each fault wedge (or line)

DP – Depth of penetration (feet)

ST – Sand thickness, feet
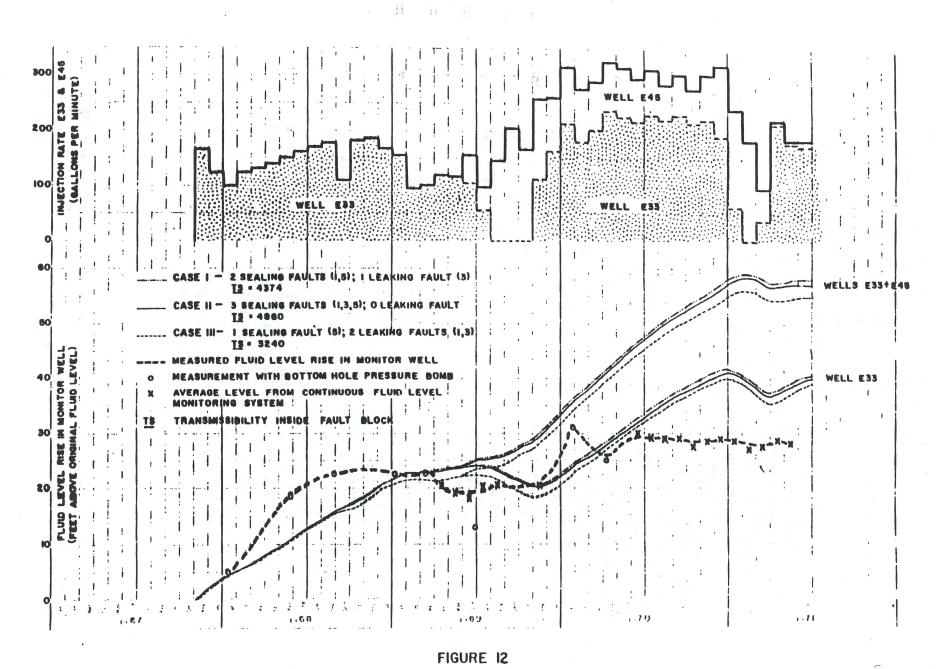
FT – Fault throw, feet

TR – Fault transmissibility

PRESSURE BUILDUP CALCULATIONS

.The presence of the pressure monitoring well at the Celanese Clear Lake plant affords the first opportunity in the area to compare calculated buildup values with measured field conditions. Figures 12 and 13 compare the monitored fluid levels with the calculated fluid levels at the monitor well under varying geologic conditions and rock properties.

After 14 months of continuous injection into Well E-33, the monitor well pressure stabilized at 22.5 feet increase with the injection rate having been maintained very nearly stable at 150 GPM for the period. The rapid early response of the monitor measurements to injection indicate that the monitor well was perforated opposite one of the more permeable zones in the injection interval and responded quickly to fluid injection. Thereafter, as this zone was pressured, other intervals began taking a larger percentage of the fluid waste. Variations in the fault leakage rate and the transmissibility were permitted in the computation until the proper combination of variables caused the calculated fluid level rise to match the measured fluid rise at the end of the 14th month within a tolerance of ± 10%. The variation in fault throw was ± 50% for each computer pass, while the variation in transmissibility was ± 10% for each computer pass. Thus, the fault system could be brought quickly to a closed or open position while the variation in transmissibility remained small. As can be seen from Figures 12 and 13, many combinations of variables can be utilized in matching the early fluid level history from the monitor well. The final choice as to the most likely values must be determined by consideration of the known geologic conditions and

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FIGURE 12

FLUID LEVEL RISE VS. TIME (I)
(CALCULATED AND MEASURED VALUES FOR MONITOR WELL)
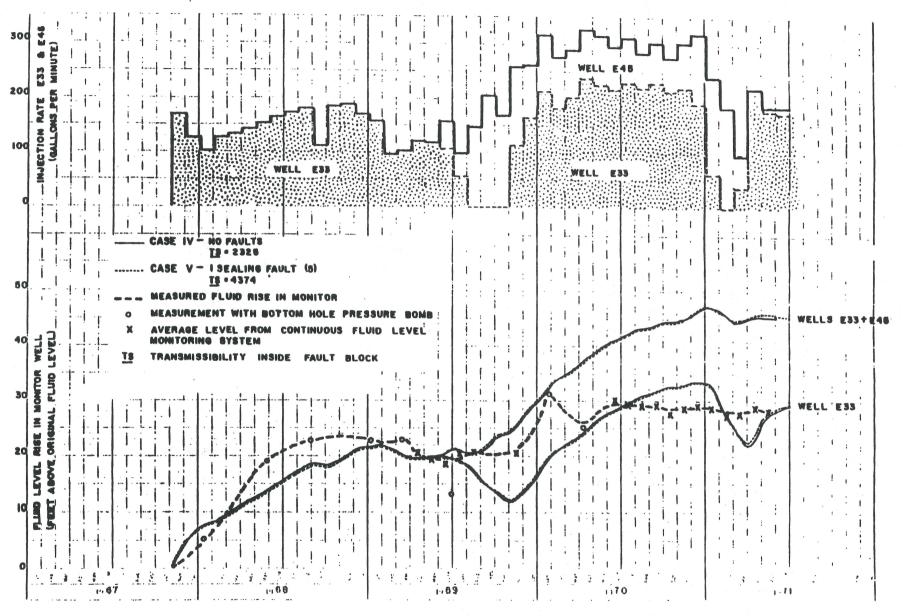
FIGURE 13

FLUID LEVEL RISE VS. TIME (2)
(CALCULATED AND MEASURED VALUES FOR MONITOR WELL)

rock properties.

Geologic control for subsurface mapping is excellent in the area from wells which have penetrated the Miocene horizon and the mapping as shown on Figure 5 is taken with confidence. Regional consideration indicates the presence of long east-west trending fault systems both north and south of the area. Core analysis from the injector well indicates a permeability of 452 millidarcies or approximately 16 Meinzer units per foot at the aquifer temperature of 140°. This air permeability analysis was determined in the laboratory of United Core, Inc., Houston, Texas. With these known conditions in mind, the best calculated fit of the computed data to the measured data was obtained in Case II where three sealing faults are indicated, with an area transmissibility of 4860.

The computed values give a good correlation with the measured data through the period February, 1970, at which time a departure in measured and computed values is observed. Several factors could account for this including:

(1) Perforations in the monitor well have become plugged and are not responsive to the fluid injection; or additional perforations are required;

(2) Zones having successively less transmissibility are receiving fluids and the 300' injection interval is not yet responsive as a unit interval;

(3) Errors in recording the fluid volume injected and/or the fluid level monitoring mechanism, could cause the deviation;
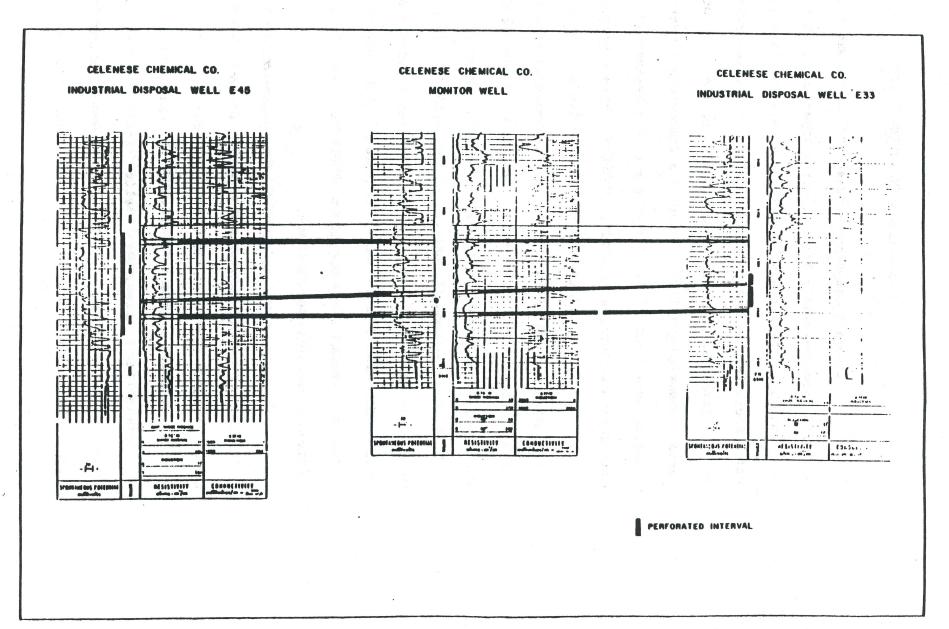
(4) The character of the injected acid fluids may have
      increased the transmissibility of the formation.

With additional monitoring and injection experience, a good
correlation between calculated and measured fluid level values would be
expected.

An electric log correlation is shown on the cross-section,
Figure 14, between the monitor well and the two injectors, E-33 and E-45.
A possible correlation of the individual sand lenses is shown, but the
magnitude of the shale intervals separating them would not be expected
to prevent hydrologic communication over a period of time.

CELENESE CHEMICAL CO.
INDUSTRIAL DISPOSAL WELL E45

CELENESE CHEMICAL CO.
MONITOR WELL

CELENESE CHEMICAL CO.
INDUSTRIAL DISPOSAL WELL E33

PERFORATED INTERVAL
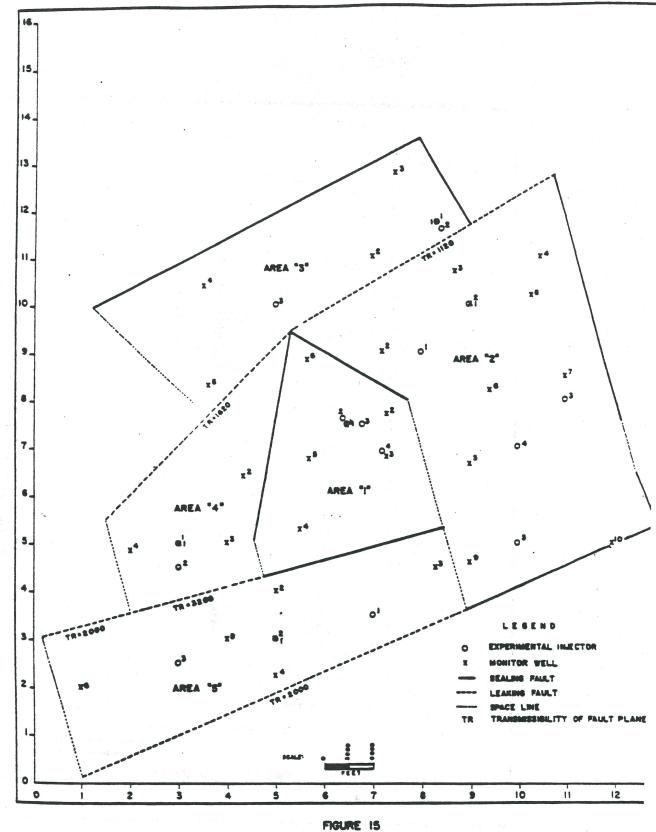
FIGURE 14

SIMULATED INJECTION SYSTEM
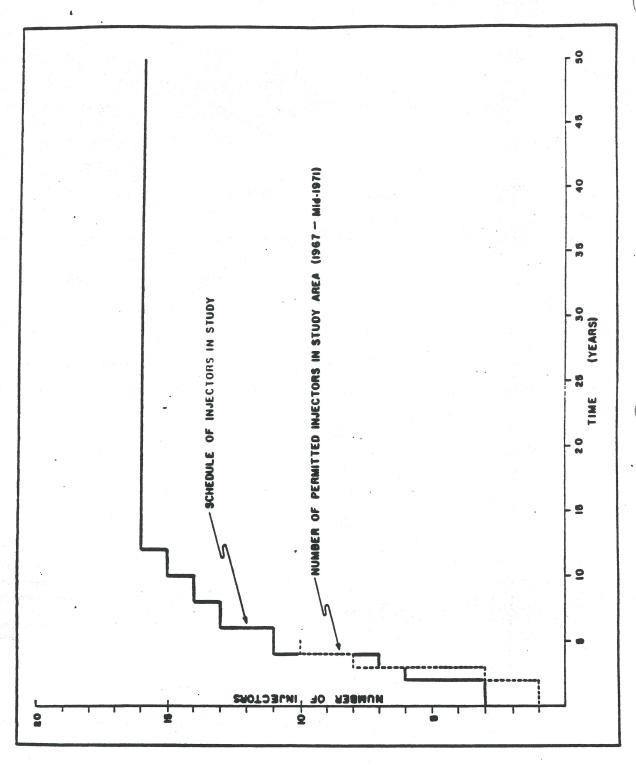
A hypothetical Miocene injection system was set up in the fault blocks surrounding Fault Block 1. This injection system is shown in Figure 15 with the location of experimental injectors and monitor points at which fluid level increases are calculated. The schedule for commencement of injection into each well is shown on Figure 16 with three injectors commencing the first year of a fifty-year injection period and increasing to a total of 17 injectors at the beginning of the 18th year. Each injector is begun at a rate of 100 GPM with a yearly increase of 2%.

It might be added here, that the Texas Water Quality Board has not permitted the intensity of injection simulated here into any single horizon. Since 1967, only five wells have been permitted to inject into the Basal Miocene member with only three wells having been completed. Well E-50, for instance (Figure 7), is permitted to inject only into the Frio horizon and all of the permitted Miocene injectors are limited as to permissible fluid level rise. Disregarding these limitations, it was desired to determine the magnitude of pressure buildup in the area under an accelerated injection program.
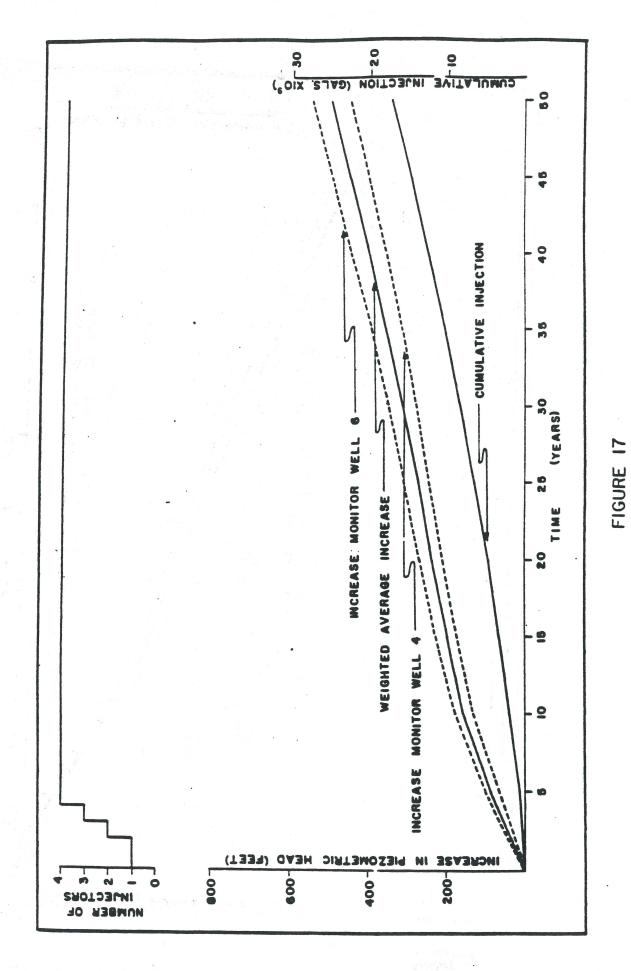
The results of the computations are shown in Figures 17, 18, 19, 20 and 21 with the maximum and minimum pressure conditions and the areally weighted pressure conditions for each fault block. Figure 22 shows the expected pressure performance in Monitor Well 5, Block 1, if this hypothetical program were realized and as influenced by the fluid inflow from Blocks 2 and 4. The sand thickness, transmissibility and storage coefficient for each block area were as follows:
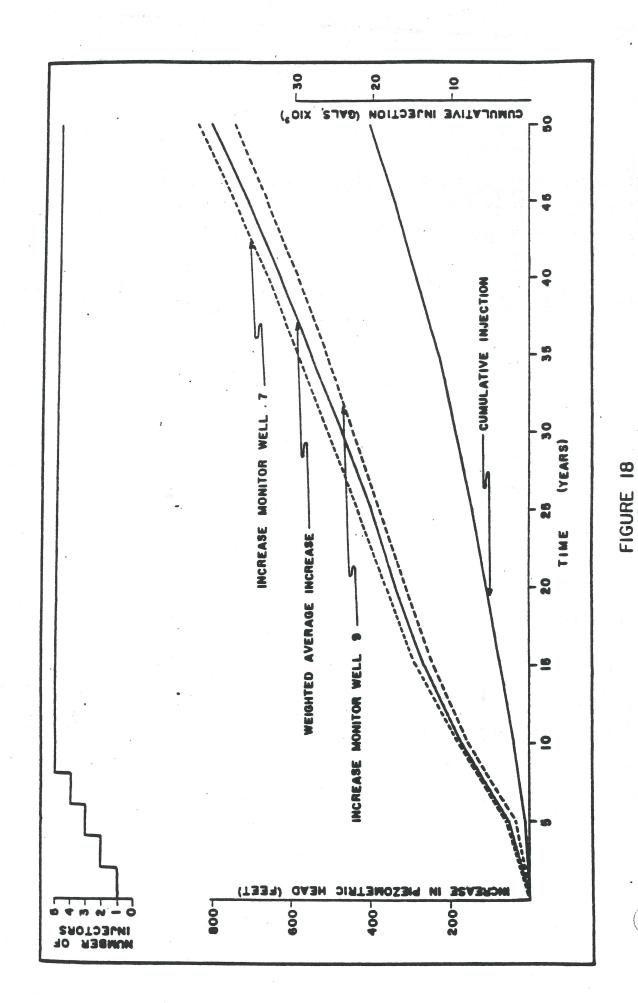
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FIGURE 15

SIMULATED INJECTION SYSTEM

FIGURE 16

FIGURE 17
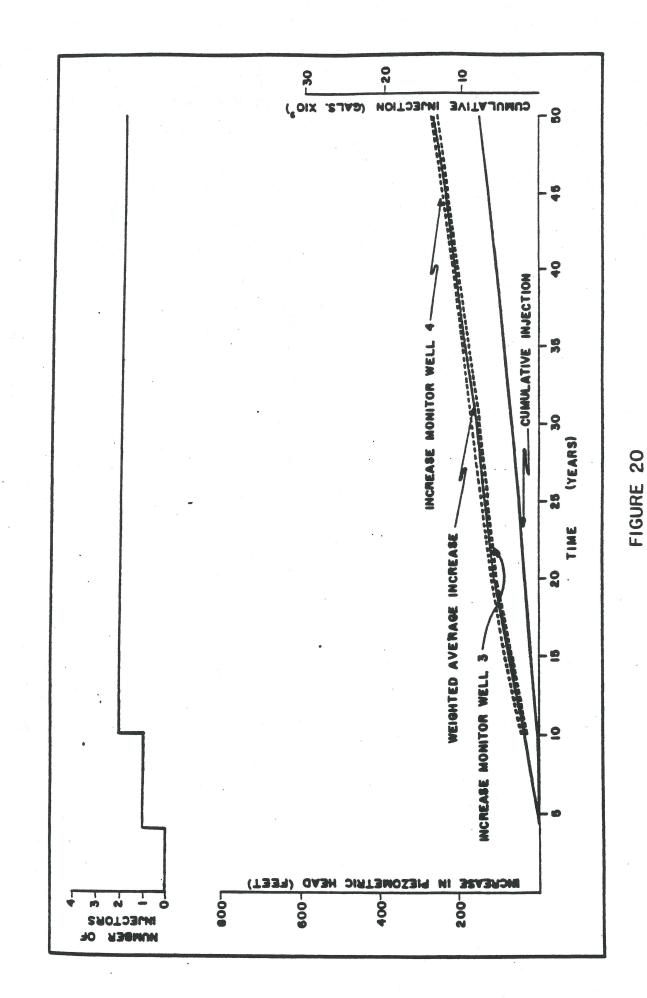
CHANGE IN PIEZOMETRIC HEAD VS. TIME

FIGURE 18

CHANGE IN PIEZOMETRIC HEAD VS. TIME

FIGURE 19

FIGURE 20

CHANGE IN PIEZOMETRIC HEAD VS. TIME
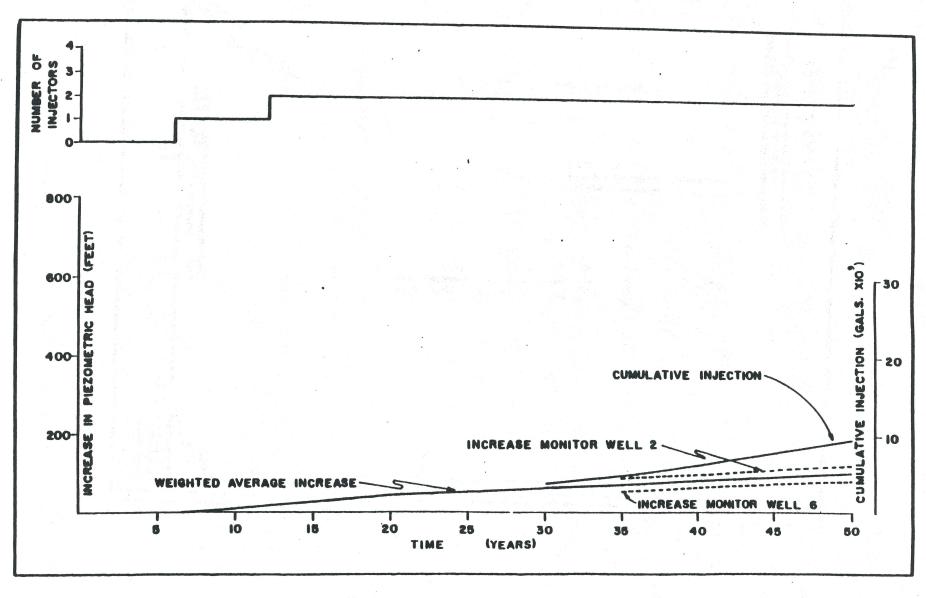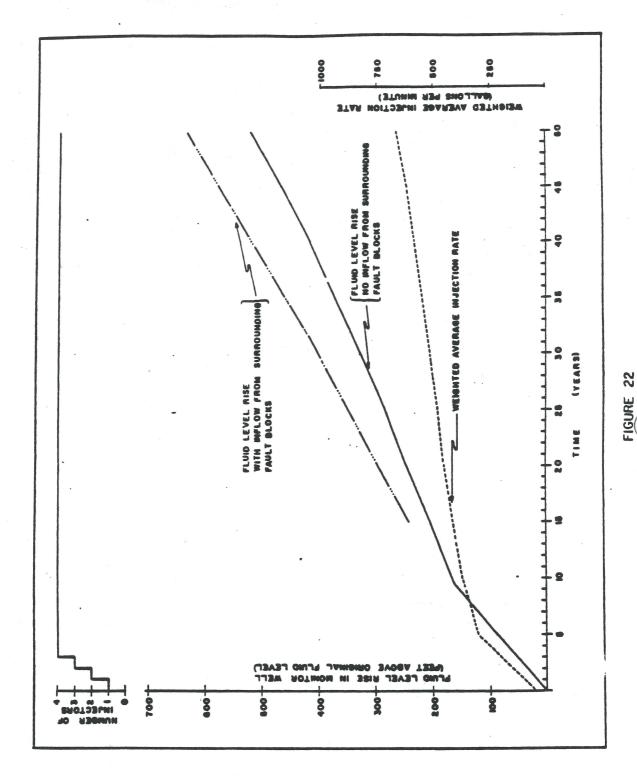
FIGURE 21

CHANGE IN PIEZOMETRIC HEAD VS. TIME

FIGURE 22

CHANGE IN PIEZOMETRIC HEAD VS. TIME
FAULT BLOCK MONITOR WELL 5

TABLE 4

ROCK PROPERTIES

BLOCK	SAND THICKNESS ST	TRANSMISSIBILITY TS	STORAGE COEFFICIENT S
1	306	4860	.001
2	258	4128	.001
3	169	2704	.001
4	298	4768	.001
5	380	6080	.001

By use of the Theis match point method, the storage coefficient S, for Block 1 was calculated to be very near .001 as determined from the early buildup data at the monitor well. This value is higher than expected, but nevertheless within the realm of possible sand and fluid properties. The same S value was utilized for the pressure buildup calculations in the adjacent fault blocks since its variation is minimized as a logarithmic value. An interesting comparison is available however in observing the volume of injected fluid in storage in each fault block area as compared with the cumulative injected volume at the end of the fifty-year injection period. This data is shown in Table 5. The volume of waste fluid calculated to be in storage was determined by use of the storage coefficient factor which was adjusted in the same proportion as the sand thickness for the particular block bore to the sand thickness in Fault Block 1. The variation in percentage of stored fluids as a result of compression of the rock material and the fluids present varied from

TABLE 5

VOLUME OF INJECTED AND STORED FLUID
SIMULATED INJECTION SYSTEM

Fault Block Area	Sand Thick. ST,FT	AREA Acres	Vol. A-F	SUM PR @ 50 yr. Ft.	PSI	Storage Coef. S	Eff. Comp. C_e [a]	Cum. Injection QT,Gal.	CALCULATED THEORETICAL STORAGE CAPACITY from S	% of QT	from C_e	% of QT
1	306	10,496	3,215,000	498.6	232.8	.001000	6.4×10^{-6}	17,132,931,000	1,705,160,000	9.95	487,000,000	2.84
2	258	28,208	7,350,000	808.3	377.4	.000843	"	20,200,663,000	6,262,759,000	31.00	1,804,516,000	8.93
3	169	14,711	2,490,000	541.0	252.6	.000552	"	12,961,680,000	1,431,269,000	11.04	409,261,000	3.16
4	298	8,967	2,675,000	264.0	123.3	.000974	"	7,578,406,000	751,166,000	9.91	214,588,000	2.83
5	380	17,025	6,475,000	100.0	46.7	.001242	"	9,343,754,000	688,969,000	7.37	196,755,000	2.11
		79,407	22,205,000					67,217,434,000	10,839,323,000	16.13		

[a]Effective Compressibility = Rock Compressibility (F_r) + Fluid Compressibility (F_w) = Pore Vol./Pore Vol./psi + Vol./Vol/psi

After Hall(5)

7 to 31% in the various fault block areas. Thus a small error would be introduced in calculating the pressure effect of one block on the other if the entire injected volume were assumed to outflow from the block.

Fault Block 2 which demonstrated the highest areally weighted buildup pressure, also reveals the largest amount of fluid in storage. This calculation implies that with the pressure buildup in the fault block approximately 31% of the total injected fluid is stored in Fault Block 2 due to compression of the reservoir rock and original fluid. Of course, all of the injected waste is stored in the area surrounding the waste disposal wells but after 50 years of injection into Block 2, 69% of the injected waste has provided storage space for itself by displacing its equivalent volume outside the block. The 31% waste balance has provided its storage space by virtue of compression of the rock and fluid material in Fault Block 2.

During the fifty-year injection period for the simulated study, a total of 67 billion gallons of waste fluid was injected. Approximately 11 billion or 16% was stored due to fluid and rock compressibility while storage for the remaining 84% of the waste fluid was provided in the injector vicinity by displacement of the original fluids. Had the five fault block areas been a completely closed system, then of course all the original and injected fluid would be stored inside the area with a correspondingly higher average buildup pressure. Only a few isolated areas in the geologic horizons studied were found to be completely closed. Thus, as would be expected, if injection were stopped, fluid migration out of the area would occur over a period of time until pressure equalization occurred between the injected area and its outlying provinces.

After 50 years of injection experience from the five block area the piezometric rise at Monitor Well #5, Fault Block 1, would have increased 634' from its original level representing a pressure increase of approximately 296 psi. A comparison of the increase in piezometric head in each of the fault blocks is shown in Figure 23 as a function of the net sand volume at the time each block had received a cumulative injected volume of 7.5 billion gallons of fluid waste. Fault conditions surrounding each fault block area were selected at random and these conditions are shown on Figure 15. Thus from Figure 23, it can be seen that there is no correlation between the expected piezometric increase and the size of the fault block into which injection takes place. Figure 24 combines the study results in a different fashion by comparison of the areally weighted pressure increase and cumulative injection into each block. Each curve terminates at the end of 50 years. Tables 6, 7, 8, 9 and show the computer results (printout) for each block area. Table 11 is an example printout from Block 2 showing the image well locations and Table 12 is a printout of the pressure buildup data from adjacent Fault Blocks 2 and 4 as measured at the monitor points in Fault Block 1.
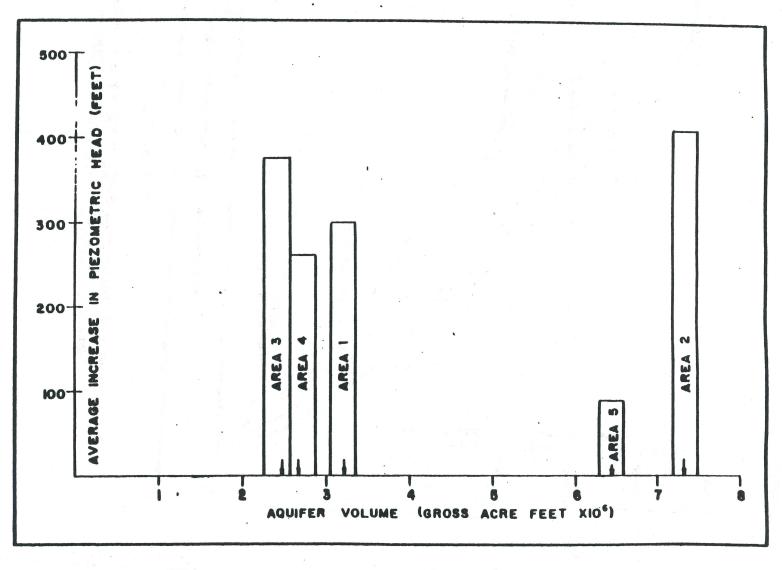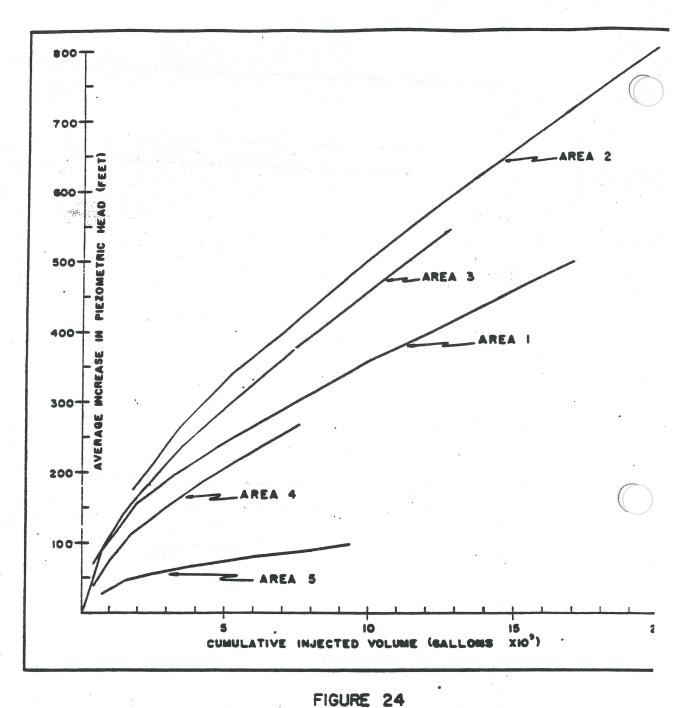
FIGURE 23

COMPARISON OF PIEZOMETRIC INCREASE FOR
EACH FAULT BLOCK IN STUDY AREA

FIGURE 24

INCREASE IN PIEZOMETRIC HEAD WITH CUMULATIVE
INJECTED VOLUME - SIMULATED STUDY AREA

TABLE 6

BLOCK 1 - 50 YEAR PRESSURE BUILDUP AT EACH
MONITOR POINT AND OUTFLOW FACTOR, F

CC= 4445.983   JJ= 1   CT= 4445.983

H+P= 196.626   JD= 1   JJ= 1   KJ=51

S+= -3.685   AP= 2   HN= 33

S+= -3.730   AP= 4   HN= 9
   CC= 4476.803   JJ= 2   CT= 8922.786

S+= -3.685   AP= 2   HN= 33

S+= -3.730   AP= 4   HN= 9
   CC= 4490.482   JJ= 3   CT= 13013.188

S+= -3.685   AP= 2   HN= 33

S+= -3.730   AP= 4   HN= 9
   CC= 4119.742   JJ= 4   CT= 17132.931

PR=	.029	T= 365.000	SUM= 635.893	KJ=51	J= 5	JJ= 4	J= 1	U=	4.970	TS= 1460.0
PR=	.019	T= 365.000	SUM= 551.139	KJ=51	J= 5	JJ= 4	JD= 2	U=	4.970	TS= 1460.0
PR=	.009	T= 365.000	SUM= 470.546	KJ=51	J= 5	JJ= 4	JD= 3	U=	4.970	TS= 1460.0
PR=	.017	T= 365.000	SUM= 449.031	KJ=51	J= 5	JJ= 4	JD= 4	U=	4.970	TS= 1460.0
PR=	.032	T= 365.000	SUM= 522.263	KJ=51	J= 5	JJ= 4	JD= 5	U=	4.970	TS= 1460.0
PR=	.065	T= 365.000	SUM= 552.256	KJ=51	J= 5	JJ= 4	JD= 6	U=	4.970	TS= 1460.0

S+= -3.685   AP= 2   HN= 33

S+= -3.710   AP= 4   HN= 9

NP= 1   F=   0.000   QA=   0.000   ICF= 1   QT= 17132.931

SLM+= 119075.566   SUMFLI= 1478941.446   NP= 2

NF= 2   F=   .771   QA=   502.561   ICF= 1   QT= 17132.931

NP= 3   F=   0.000   QA=   0.000   ICF= 1   QT= 17132.931

SLM+= 338865.880   SUMFLI= 1478941.446   NP= 4

NF= 4   F=   .229   QA=   149.377   ICF= 1   QT= 17132.931

DEFINITION OF TERMS

PR - Incremental increase (or decrease) in
     piezometric head from real or image
     well, gpm
T - Number of days since injection began
     to time of pressure determination
SUM - Algebraic sum of PR values at each
     monitor point location, JD
KJ - Counter for cumulative time period
J - Image well number
JJ - Number of real injectors
JD - Monitor point number
QD - Incremental difference in rate of
     recharge or discharge, gpm
TS - Average transmissibility of sand in
     fault block, gallons/day/foot
NP - Number of fault line
F - Outflow factor
QA - Outflow across individual line

TABLE 7

BLOCK 2 – 50 YEAR PRESSURE BUILDUP AT
EACH MONITOR POINT AND OUTFLOW FACTOR, Y

PR=	.02	T= 305.000	SUM= 467.753	K3=51	J= 4	JJ= 5	JD= 1	Y=	-.600	
PR=	.001	T= 305.000	SUM= 789.053	K3=51	J= 4	JJ= 5	JD= 2	Y=	-.600	TS=
PR=	.001	T= 305.000	SUM= 798.121	K3=51	J= 4	JJ= 5	JD= 3	Y=	-.600	TS=
PR=	.003	T= 305.000	SUM= 790.332	K3=51	J= 4	JJ= 5	JD= 4	Y=	-.600	TS=
PR=	.025	T= 305.000	SUM= 806.037	K3=51	J= 4	JJ= 5	JD= 5	Y=	-.600	TS=
PR=	.025	T= 305.000	SUM= 825.970	K3=51	J= 4	JJ= 5	JD= 6	Y=	-.600	TS=
PR=	.15	T= 305.000	SUM= 843.625	K3=51	J= 4	JJ= 5	JD= 7	Y=	-.600	TS=
PR=	.006	T= 305.000	SUM= 448.562	K3=51	J= 4	JJ= 5	JD= 8	Y=	-.600	TS=
PR=	.005	T= 305.000	SUM= 738.342	K3=51	J= 4	JJ= 5	JD= 9	Y=	-.600	TS=
PR=	.67	T= 305.000	SUM= 749.042	K3=51	J= 4	JJ= 5	JD=10	Y=	-.600	TS=

S= -2.477 NP= 2 YP= 21

S= -2.685 NP= 3 YP= 33

S= .610 NP= 5 YP= 56

S= .585 NP= 6 YP= 28

S= -3.741 NP= 8 YP= ..

NP= 1 F= 0.000 QA= .000 ICR= 2 QT= 20200.643
SUM= 400478.083 SUMFLT= 3871223.042 NP= 2

NP= 2 F= .244 QA= 167.536 ICR= 2 QT= 20200.643
SUM= 1447266.755 SUMFLT= 3871223.042 NP= 3

NP= 3 F= .340 QA= 291.730 ICR= 2 QT= 20200.643

NP= 4 F= 0.033 QA= 0.000 ICR= 2 QT= 20200.643
SUM= 613134.207 SUMFLT= 3871223.042 NP= 5

NP= 5 F= .158 QA= 121.745 ICR= 2 QT= 20200.643
SUM= 270714.454 SUMFLT= 3871223.042 NP= 6

NP= 6 F= .076 QA= 95.342 ICR= 2 QT= 20200.643

NP= 7 F= 0.000 QA= 0.000 ICR= 2 QT= 20200.643
SUM= 565025.239 SUMFLT= 3871223.042 NP= 8

NP= 8 F= .100 QA= 112.311 ICR= 2 QT= 20200.643

NP= 9 F= 0.000 QA= 0.000 ICR= 2 QT= 20200.643

DEFINITION OF TERMS

PR – Incremental increase (or decrease) piezometric head from real or image gm

T – Number of days since injection time of pressure determined

SUM – Algebraic sum of PR values point location, JD

K3 – Counter for cumulative time period

J – Image well number

JJ – Number of real injectors

JD – Monitor point number

QD – Incremental difference in rate or discharge, gpm

TR – Average transmissibility of sand block, gallons/day/foot

NP – Number of fault line

F – Outflow factor

QA – Outflow across individual line

ICR – Fault block number or area number

QT – Cumulative injection – all injectors this block

TABLE 8

BLOCK 3 - 50 YEAR PRESSURE BUILDUP AT EACH MONITOR POINT AND OUTFLOW FACTOR, F

PR=	.015	T=	365.000	SUM=	919.335	K3=51	J= 4	JJ= 7	JD= 1	JD=	4.470	TS=	2700.0
PR=	.003	T=	365.000	SUM=	637.257	K3=51	J= 4	JJ= 7	JD= 2	QD=	4.470	TS=	2700.0
PR=	.005	T=	365.000	SUM=	716.524	K3=51	J= 4	JJ= 7	JD= 3	QD=	4.470	TS=	2700.0
PR=	.000	T=	365.000	SUM=	422.032	K3=51	J= 4	JJ= 7	JD= 4	QD=	4.470	TS=	2700.0
PR=	.003	T=	365.000	SUM=	356.030	K3=51	J= 4	JJ= 7	JD= 5	QD=	4.470	TS=	2700.0

$S_F = .6\ 0$ $NP= 1$ $N= 52$

$S_F = 1.35$ $NP= 2$ $N= 29$

$S_F = -.979$ $NP= 3$ $N= 39$

SUM= 565032.146   SUMFLI= 2003242.705   NP= 1

NF= 1   F= .271   QA= 133.773   ICE= 3   QT= 12941.690

SUM= 454166.340   SUMFLI= 2003242.705   NP= 2

NF= 2   F= .210   QA= 107.525   ICE= 3   QT= 12941.690

SUM= 1084044.212   SUMFLI= 2003242.705   NP= 3

NF= 3   F= .511   QA= 251.716   ICE= 3   QT= 12941.690

NF= 3   F=   QA=   ICE= 3   QT= 12941.690

DEFINITION OF TERMS

PR – Incremental increase (or decrease) in piezometric head from real or image well, gpm

T – Number of days since injection began to time of pressure determination

SUM – Algebraic sum of PR values at each monitor point location, JD

K3 – Counter for cumulative time period

J – Image well number

JJ – Number of real injectors

JD – Monitor point number

QD – Incremental difference in rate of recharge or discharge, gpm

TS – Average transmissibility of sand in fault block, gallons/day/foot

NP – Number of fault line

F – Outflow factor

QA – Outflow across individual line

ICE – Fault block number or area number

QT – Cumulative injection – all injectors this block

TABLE 9

BLOCK 4 - 50 YEAR PRESSURE BUILDUP AT EACH
MONITOR POINT AND OUTFLOW FACTOR, F

DEFINITION OF TERMS

PR - Incremental increase (or decrease) in piezometric head from real or image well, gpm

T - Number of days since injection began to time of pressure determination

SUM - Algebraic sum of PR values at each monitor point location, JB

KJ - Counter for cumulative time period

JJ - Image well number

JJ - Number of real injectors

JB - Monitor point number

QP - Incremental difference in rate of recharge or discharge, gpm

TR - Average transmissibility of sand in fault block, gallons/day/foot

MP - Number of fault line

F - Outflow factor

QA - Outflow across individual line

TABLE 10

BLOCK 5 - 50 YEAR PRESSURE BUILDUP AT EACH
MONITOR POINT AND OUTFLOW FACTOR, F

PR=	.054	T=	365.000	SUM=	150.786	K3=51	J= 7	JJ= 7	JD= 1	QD=	3.020	TS=	3041.0
PR=	.073-	T=	365.000	SUM=	121.731	K3=51	J= 2	JJ= 7	JD= 2	QD=	3.020	TS=	3041.0
PR=	.013	T=	365.000	SUM=	74.473	K3=51	J= 7	JJ= 7	JD= 3	QD=	3.020	TS=	3041.0
PR=	.144	T=	365.000	SUM=	114.437	K3=51	J= 2	JJ= 7	JD= 4	QD=	3.020	TS=	3041.0
PR=	.043	T=	365.000	SUM=	117.490	K3=51	J= 7	JJ= 7	JD= 5	QD=	3.020	TS=	3041.0
PR=	.053	T=	365.000	SUM=	42.126	K3=51	J= 7	JJ= 7	JD= 6	QD=	3.020	TS=	3041.0

SP=   -3.477   AP= 1   M= 21

SP=   .447   AP= 2   M=103

SP=   -7.615   AP= 3   M= 35

SP=   .309   AP= 4   M= 22

SP=   .293   AP= 5   M= 34

SLMP=   420347.139   SUMFLT=   2252941.467   NP= 1

NP= 1   F=   .149   QA=   57.599   ICE= 5   QT= 9363.754

SLMP=   567247.771   SUMFLT=   2252941.467   NP= 2

NP= 2   F=   .252   QA=   95.529   ICE= 5   QT= 9363.754

SLMP=   724408.711   SUMFLT=   2252941.467   NP= 3

NP= 3   F=   .323   QA=   114.953   ICE= 5   QT= 9363.754

SLMP=   157933.146   SUMFLT=   2252941.467   NP= 4

NP= 4   F=   .073   QA=   24.624   ICE= 5   QT= 9363.754

SLMP=   319955.130   SUMFLT=   2252941.467   NP= 5

DEFINITION OF TERMS

PR - Incremental increase (or decrease) in piezometric head from real or image well, gpm

T - Number of days since injection began to time of pressure determination

SUM - Algebraic sum of PR values at each monitor point location, JD

K3 - Counter for cumulative time period

J - Image well number

JJ - Number of real injectors

JD - Monitor point number

QD - Incremental difference in rate of recharge or discharge, gpm

TS - Average transmissibility of sand in fault block, gallons/day/foot

NP - Number of fault line

F - Outflow factor

QA - Outflow across individual line

ICE - Fault block number or area number

QT - Cumulative injection - all injectors

TABLE 11

EXAMPLE OF IMAGE WELL LOCATIONS,
XA(J), YA(J) FOR INJECTOR
JJ1, BLOCK 2

CC= 575.521   JJ= 1   CT= 575.521

XA(J)= 61457.947   YA(J)= 63403.296J= 2
A R= 5198.477   BP= 5926.453   NP= 4   ANGL= 30.656   JJ= 1
A= -.593   M= 1K= 1   NP= 0

XA(J)= 37423.343   YA(J)= 72114.970J= 3
AR= -9057.661   BP= 10590.562   NP= 4   ANGL= -31.217   JJ= 1
A= .696   M= 2K= -1   NP= 0

XA(J)= 25487.261   YA(J)= 71678.862J= 4
AR= -13935.066   BP= 16170.560   NP= 4   ANGL= -31.217   JJ= 1
A= .696   M= 3K= -1   NP= 0

XA(J)= 20795.832   YA(J)= 66732.806J= 5
AR= 13691.294   BP= 15916.715   NP= 4   ANGL= 30.656   JJ= 1
A= -.593   M= 4K= 1   NP= 0

XA(J)= 15477.425   YA(J)= 55427.307J= 6
AR= 8024.616   BP= 9333.300   NP= 4   ANGL= 30.656   JJ= 1
A= -.593   M= 1K= 1   NP= 0

J= 2

J= 4

XA(J)= 37545.878   YA(J)= 72641.230J= 2
AR= -9321.744   BP= 10799.611   NP= 4   ANGL= -30.343   JJ= 1
A= .585   M= 1K= 1   NP= 0

XA(J)= 94045.443   YA(J)= 85015.055J= 3
AR= -5711.133   BP= 22075.844   NP= 4   ANGL= 75.021   JJ= 1
A= -2.734   M= 2K= -1   NP= 0

XA(J)= 94792.647   YA(J)= 67517.037J= 4
AR= -7180.922   BP= 27741.563   NP= 4   ANGL= 75.021   JJ= 1
A= -3.734   M= 3K= -1   NP= 0

XA(J)= 67433.335   YA(J)= 14438.240J= 5
AR= 19454.941   BP= 22466.029   NP= 4   ANGL= -30.343   JJ= 1
A= .585   M= 4K= 1   NP= 0

J= 2

J= 4

XA(J)= 33243.293   YA(J)= 64940.740J= 2
AR= -7029.099   BP= 18070.422   NP= 9   ANGL= 66.596   JJ= 1
A= -2.310   M= 1K= 1   NP= 0

XA(J)= 79438.561   YA(J)= 66331.111J= 3
AR= 29166.961   BP= 31854.447   NP= 9   ANGL= -23.739   JJ= 1
A= .640   M= 2K= -1   NP= 0

XA(J)= 107764.007   YA(J)= 10476.676J= 4
AR= 29446.321   BP= 31697.373   NP= 9   ANGL= -23.739   JJ= 1
A= .640   M= 3K= -1   NP= 0

DEFINITION OF TERMS

XA(J) – Horizontal coordinate
         well, feet

YA(J) – Vertical coordinate of
         well, feet

J – Image well number

TABLE 12

SUMMATION OF PRESSURE BUILDUP, SUMT, FROM ADJACENT
BLOCKS (2,4) AT BLOCK 1 MONITOR POINTS (JD)

TR= 4860.0   IA= 2
BLINE= 16680.0   IA= 2

TR= 4860.0   IA= 4
BLINE= 4616.0   IA= 4
SUMT=   643.075   SUMPRS=   132.536   JD= 2   K3=51   ICE= 1

TR= 4860.0   IA= 2
BLINE= 16680.0   IA= 2

TR= 4860.0   IA= 4
BLINE= 4616.0   IA= 4
SUMT=   617.259   SUMPRS=   146.713   JD= 3   K3=51   ICE= 1

TR= 4860.0   IA= 2
BLINE= 16680.0   IA= 2

TR= 4860.0   IA= 4
BLINE= 4616.0   IA= 4
SUMT=   559.116   SUMPRS=   109.286   JD= 4   K3=51   ICE= 1

TR= 4860.0   IA= 2
BLINE= 16680.0   IA= 2

TR= 4860.0   IA= 4
BLINE= 4616.0   IA= 4
SUMT=   634.444   SUMPRS=   112.181   JD= 5   K3=51   ICE= 1

TR= 4860.0   IA= 2
BLINE= 16680.0   IA= 2

TR= 4860.0   IA= 4
BLINE= 4616.0   IA= 4
SUMT=   648.614   SUMPRS=   96.358   JD= 6   K3=51   ICE= 1

DEFINITION OF TERMS

TR – Fault transmissibility
IA – Counter for designating contributing line
BLINE – Length of leaking fault line or space line
SUMT – Total pressure buildup at monitor point
SUMPRS – Pressure buildup contribution from adjacent fault blocks
JD – Monitor point number
K3 – Counter for cumulative time period
ICE – Fault block number or area number

DISCUSSION

No consideration was given to the gravity effect or hydros head in the hypothetical buildup case just presented. The maximum gravity head can be added to any individual monitor point for a more exact solution. The concern here was to determine the pressure effect of injection and not to consider the forces already balanced by nature.

The study area shows a maximum structural relief of approximately 1,000' in an individual fault block and a minimum relief of 400'. The path of the effluent waste in an injection area is toward the area o least hydrostatic pressure relative to its location. This will usually be reflected in increased well-head injection pressure (neglecting friction) equivalent to the highest hydrostatic head acting against it. As these pressures become equalized (up-dip and down-dip), then a truer radial flow pattern is developed.

In most of the area the gravity head is small and can be neglected for distances in the range of two to three miles. As an example the top perforations in Injector E-33 are 43' below the bottom perforations in the monitor well, but an increase in piezometric head in the monitor well was detected almost immediately. The wells are 6,250' apart. This reflects the pressure response in a fluid-filled system where the effect of storage due to compression is very small within the magnitude of early pressures observed in the study.

Sheets (12) describes the case of two active surface faults in the Houston area which can be traced to the subsurface depth of the Bas Miocene. These faults are located in the Fairbanks Oil Field and the

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Clinton Oil Field which are northwest and east of Houston respectively. The fault movement is continuous and reaches a rate of approximately one inch per year. Sheets contends that these faults are caused by uplift of relatively plastic salt as opposed to rigid basement rocks as in other areas. He discounts the effect of surface subsidence in the area (due to ground water pumping) in causing active surface faulting, but concedes that such surface warping may have triggered or accelerated the surface movement of some of the active faults.

The placement of an injection well very near the subsurface location of a fault should certainly be avoided since the differential pressure exerted on the formation at this point may reach several hundred pounds per square inch. It is interesting to observe (Figure 1) the gradient profile of the fresh water-salt water interface in the area as this interface approaches the seashore. Winslow, Doyel and Wood (20) describe the seaward profile of ground water in the Houston area as it approximates the profile as predicted by the Ghyben-Herzberg theory. Thus if a salt water aquifer were communicated by leaking faults extending to the surface, a major disruption in this profile would be expected. The separation of the ground water from the deeper salt water aquifers can be assured when consideration is given to the fact that the piezometric head for the Basal Miocene aquifer in the area extends to near the surface whereas the fresh water interface exists as deep as 2600' below the surface. Obviously a leaking fault extending to near the surface would have permitted the pumping of salt water in the same area where fresh water is now obtained.

The maximum pressure increase due to injection in the hypothetical study amounted to an increase of 300-400 psi in the five fault blocks of the study area. The natural piezometric gradient in the study area is .467 psi per foot and a pressure increase of this magnitude would increase the piezometric gradient to .55 psi per foot for a Basal Miocene zone at a depth of 5,000'. The resulting piezometric head is well below the hydraulic fracturing gradient experienced in the area which varies from .6 to .8 psi per foot (1, 13, 14). This fracture gradient applies to those formations which have not been pressured due to injection. Eaton (1) gives an interesting example of an injection well which was hydraulic fractured at six-month intervals with the necessary fracture gradients successively increasing from .748 to .864 to .993 psi per foot as injection into the formation continued. The point made here is that waste fluids can be safely confined if intelligent operation is applied. With waste disposal into a thin sand interval, more care must be used if there is only a short vertical separation between the disposal zone and a zone of usable brackish water or fresh water lying above.

Hubbert & Willis (8), in their classic paper on hydraulic fracturing, point out that the shearing mechanism of faulting is quite distinct from the tension phenomena which produces hydraulic fracturing. The analogy brought in their discussion derives from a consideration of the magnitude of earth forces necessary to be overcome while inducing a fracture or fault. In the Houston area where normal faulting is taking place, the greatest stress should be approximately vertical (1.0 psi/foot) and equal to the effective pressure of the overburden, while the least stress should be horizontal and most probably between one-half and

one-third the effective pressure of the overburden. The Tertiary s
ments of the Texas Gulf coast have undergone recurrent normal faulting
throughout Tertiary time and up to the present. Except around the salt
domes, the faults are mostly parallel to the strike of the rock and thu
the axis of least stress must be parallel to the dip.

Subsurface rocks along the Gulf coast have experienced much
higher confinement pressures than would be dictated by consideration of
minimum rock strength properties. These "geopressured" reservoirs exis
all along the Gulf Coast area with piezometric gradients ranging from
approximately .5 psi per foot to as high as .960 per foot. The mechani
of geopressure will not be gone into here, but is mentioned to illustra
that under certain conditions these sedimentary rocks have a pressure
capacity equal nearly to the overburden gradient. The closest exam
of a geopressured condition is described by Fowler (4) just to the sout
west of the study area in the Chocolate Bayou Field, Brazoria County,
Texas.

It is obvious from this discussion that the pressure capacity
of zones of waste confinement may vary over a large range and still be
repositories of safekeeping. However the dry holes in the Houston-
Galveston area which were drilled with insufficient surface casing and
which were improperly plugged will continue to control the maximum per-
missible injection rate, thus limiting the safe capacity for injection.
Insufficient surface casing or improper plugging results in inadequate
protected fresh water sands. The dry holes were plugged by filling wi
a heavy mud and by capping near the surface with cement or a welded
The Texas Water Quality Board has permitted a pressure tolerance of .0